Pbar acceleration in the MI using 2.5 MHz and 53 MHz rf Systems

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Version-4

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Abstract

Here we present the results of beam dynamics simulations and beam studies in the Main injector on an 8-150 GeV pbar acceleration scheme. The scheme involves accelerating four 2.5 MHz bunches from 8-27 GeV using the MI 2.5 MHz (h=28) rf system, a harmonic beam transfer at 27 GeV front porch from 2.5 MHz to 53 MHz rf buckets after a bunch rotation and an acceleration from 27-150 GeV using the 53 MHz (h=588) rf system. This scheme is expected to give less than 50% longitudinal emittance growth while the currently used 53 MHz bunch coalescing scheme at 150 GeV which gives rise to an emittance growth in the range of 100-140%. Simulations are carried out for the new acceleration scheme for bunches with emittance in the range 0.8-2.8 eVs/bunch and intensities of 60E9-170E9. The simulations predict about 20% emittance growth. The beam studies have been performed for single and four bunch scenarios in the MI using protons from the Booster for the beam intensity of 20-60E9/bunch and initial longitudinal emittance of 0.8-2 eVs. The outcome of the beam studies is very promising. The data show that acceleration efficiency is about 100%, emittance growth for single-bunch scenario is about 30% and emittance growth for the four-bunch scenario is 45% for beam acceleration from 8 GeV up to the end of the harmonic transfer at 27GeV. The beam studies of acceleration from 27-150 GeV are in progress and we do not expect any emittance growth in this part of the cycle.

Contents

1. Project Goal

The goal of the Fermilab Run II upgrade is to maximize integrated luminosity delivered to the collider experiments. In this effort the preservation of the beam bunch emittance through the accelerator chain is very important [1,2]. The Run II parameters call for the rms bunch length of pbars at the Tevatron interaction points to be 0.5 m or less with 1 MV of rf voltage. This corresponds to a bunch longitudinal emittance less than 2.5 eVs. At present, the longitudinal emittance of the pbar bunches at 150 GeV in the Tevatron is about 1.5 times larger than Run II goals. Beam coalescing at 150 GeV (the method currently in use) in the Main Injector (MI) alone gives rise to longitudinal emittance dilution by a factor of two or more. In the proposed "2.5 MHz acceleration" scheme, the pbars from the Recycler or the Accumulator will be accelerated in the MI using the 2.5 MHz rf system (h=28) from 8GeV to 27GeV. At 27GeV the bunch is rotated and transferred to a 53 MHz rf (h=588) bucket and then accelerated to 150 GeV using 53MHz rf system. This method is expected to give the longitudinal emittance dilution to less than 50% with no beam loss in the Main Injector.

The pbar beam properties in the MI at 8 GeV injections are assumed as

i. four 2.5MHz pbar bunches are separated by 397 ns per MI acceleration cycle and there will be a total of nine acceleration cycles needed per ppbar store in the Tevatron.
ii. the longitudinal emittance of each 2.5MHz bunch is in the range of 0.8 eVs to 3 eVs
iii. bunch intensities are in the range of 50E9 to 170E9 pbars/bunch[1]

Then, at 150 GeV in the MI before injection into the Tevatron, we expect to have

i. bunch separation as at 8 GeV (i.e., 397nsec),
ii. the longitudinal emittance <1.5 times the 8 GeV values, and,
iii. bunch intensities same as at 8 GeV i.e., no beam loss.

[1] At the time of approval of the beam studies on acceleration using 2.5 MHz rf system, *i.e.*, in mid-2002, the max. pbar intensity goal per bunch was 60E9 with 397 nsec bunch spacing [Mike Church and Shekhar Mishra, private communications and reference 2] . Over the last one year the Run II upgrade project evolved and a new intensity goal of 170E9 pbar/bunch [1] has been set.

2. Introduction – why do we need a new pbar acceleration scheme in the MI

During the collider Run I and until now in Run II, we have adopted standard multi-bunch (five to nineteen 53 MHz bunches) coalescing at 150 GeV to produce high intensity pbar bunches. In this current scheme, the pbars are extracted from the Accumulator Ring using the ARF4 rf system (Accumulator 2.5 MHz rf system) in four bunches of initial desired longitudinal emittance. Next, each 2.5MHz bunch is re-bunched using ARF1 rf system (Accumulator 53 MHz rf system) into 5 to 19 smaller bunches (the number of 53 MHz bunches depends on the initial longitudinal emittance of the 2.5 MHz bunches). These bunches are transferred to the matched Main Injector (MI) 53 MHz rf buckets at 8 GeV. The four groups of 53 MHz bunches (with center to center separation=397nsec) are accelerated from 8 GeV to 150 GeV in the MI. Finally, each group of pbar bunches is coalesced into one 53MHz bunch using the MI 2.5MHz rf system and four such pbar bunches are injected into the Tevatron per transfer. To have 36 pbar bunches in Tevatron, there will be a total of nine transfers of this type. Thus, each pbar bunch in a 53MHz bucket at 150 GeV before transfer to the Tevatron undergoes rf manipulations pertaining to bunching in the Accumulator and coalescing in the MI. The coalescing alone is found to introduce about a factor of two longitudinal

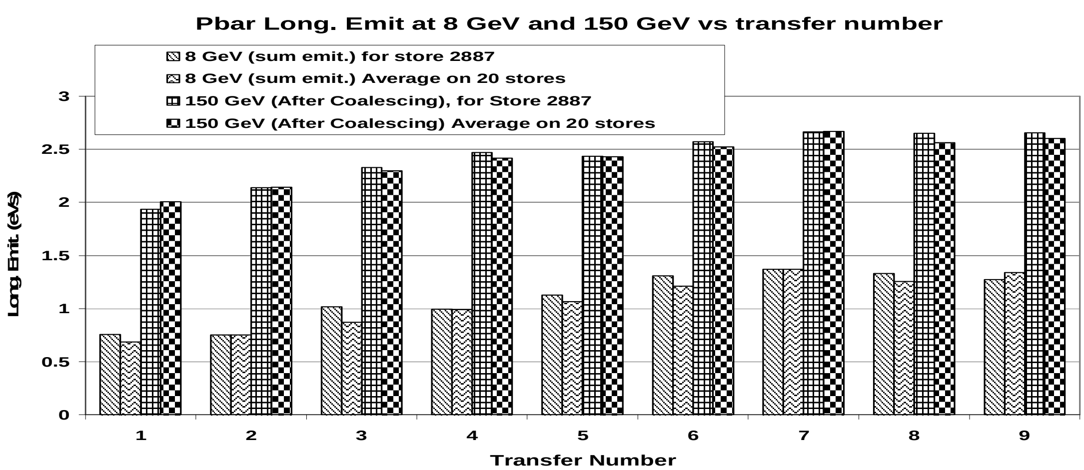

Figure 1. Pbar longitudinal emittance before and after coalescing in the existing collider operation. The data shown is average of pbar long. emit. (sum over all four groups of 53 MHz bunches) measured in the Main Injector at 8 GeV and at 150 GeV after coalescing for the last 20 stores in the Tevatron ending with store-2998. Similar data for store-2887, which had the highest peak luminosity of about 49E30cm^{-2}/sec of all the stores so far is also shown.

emittance dilution besides the one arising from 53 MHz capture in the Accumulator and transition crossing in the MI. Figure 1 shows the SDA data for the pbar sum longitudinal emittance/group at 8 GeV in the MI and at 150 GeV (just before transfer to the Tevatron) vs. transfer number for several recent ppbar stores in the Tevatron. On the average we see longitudinal emittance dilution of about a factor of 2.4[2]. It is very evident that at low pbar emittance (~0.7 eVs/group of 53 MHz bunches) we observe a factor of three emittance growth in the MI. Figure 2 shows the coalescing efficiency, a measure of pbar beam particles left in the 53 MHz rf bucket before and after coalescing, as a function of the pbar transfer number. This clearly demonstrates that we loose up to 15% pbars during the coalescing[3].

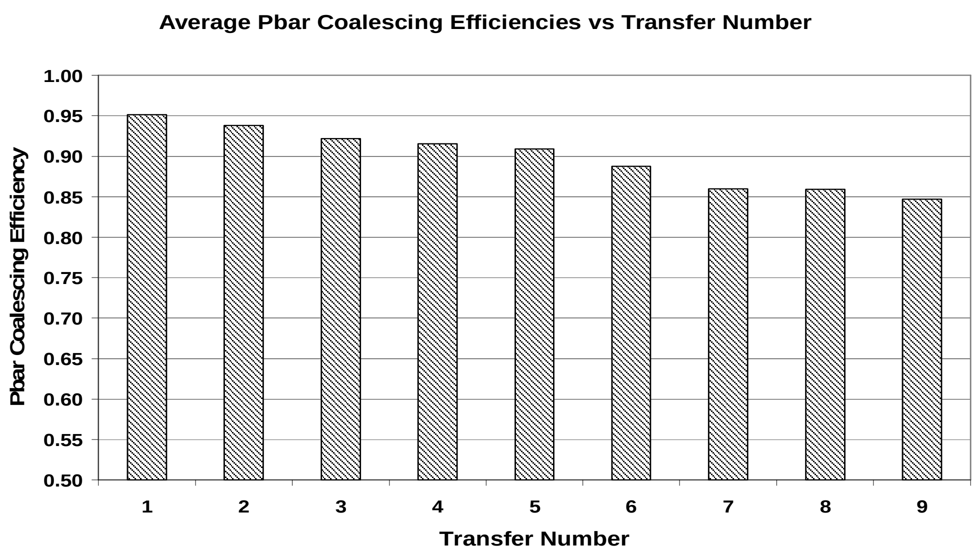

Figure 2. Average Pbar coalescing efficiencies for the last 20 stores ending with store-2998. The coalescing efficiency measures the fractional beam particles left in the final bunch at 150 GeV. The 2.5 MHz acceleration scheme explained in this report would expect have efficiency to be unity in this scale for all transfers.

This undesirable longitudinal emittance growth can be minimized to a level <50% of that at injection with no beam loss, using a combination of 2.5 MHz and 53 MHz

[2] This factor include longitudinal emittance dilution arising from the coalescing as well as the beam-loading effects.

[3] Notice that, typically, more than nine pbar 53MHz bunches/group are injected during the last few pbar transfers from the Accumulator into the MI. This is because of larger long. emittance compared with previous transfers. These have considerable effect on the over-all coalescing efficiency. If the number of pbar bunches reduced to 9 or less per group we expect better coalescing efficiency.

acceleration [2-4] in the MI. This scheme also helps to increase the collider luminosity by

1) ~10% by sending 10% more pbars to the Tevatron
2) ~7% through Hourglass factor by sending low emittance pbar bunches.

We will have other added advantages due to low emittance pbars to the Tevatron *viz.*, 1) the extent of the interaction region scales as square-root of the longitudinal emittance and a shorter interaction region gives better collision coverage at the collider detectors, 2) a better transfer efficiency in A150 beam-line and 3) increased acceleration efficiency in the Tevatron by reducing longitudinal shaving.

3. pbar Acceleration using 2.5 MHz (h=28) and 53 MHz (h=588) rf systems

The acceleration scheme described here assumes that the pbar beam is coming either from the Recycler (RR) or the Accumulator. For pbars from the Recycler, the pbar bunches are produced using a RR broadband barrier bucket system [5]. Four 2.5 MHz

Table–I: The pbar beam and machine parameters for the Recycler Ring and Accumulator

Parameters	Recycler Ring	Accumulator
Pbar Bunch Intensity	50E9-170E9	50E9
Invariant 95% bunch long. emittance/bunch[6]		
With stochastic cooling alone	2.7 eVs	0.5-1.8 eVs
With electron and stochastic cooling	0.83 eVs	
Beam Energy	8.938 GeV	8.938 GeV
Max. 2.5 MHz RF voltage	2 kV	1000V
RF frequency	2.5 MHz	2.5 MHz
Bucket half height	6.8 MeV	10 MeV
Bucket Area	3.44 eVs	5.23 eVs

bunches are created using a 2 kV sinusoidal rf wave [2]. The maximum area of a 2.5 MHz rf bucket is about 3.44 eVs/bucket. We expect that the pbar bunches to have longitudinal emittance in the range of 0.8 – 3 eVs/bunch [2, 6] . The pbar beam bunches are transferred to the MI 2.5 MHz matched rf buckets. The RF and beam parameters at the stage of injection into the MI are summarized in Table –I.

For pbars arising from the Accumulator Ring, the longitudinal emittance per 2.5MHz bunch at 8 GeV can be as low as 0.5 eVs with a maximum intensity of about 40E9 pbars/2.5 MHz bunch. For the nine transfers, the emittance are in the range of 0.5-1.5eVs as shown in figure 1.

a) MI Acceleration Ramp:

Figure 3 shows the complete sequence of the present acceleration scheme. A train of four 2.5 MHz bunches are accelerated from 8 GeV to 27 GeV using the shown MI momentum (P (GeV/c)) ramp and the "coalescing RF system" (here after we refer it as "2.5 MHz rf system"). The maximum available peak rf voltage from 2.5MHz rf system is

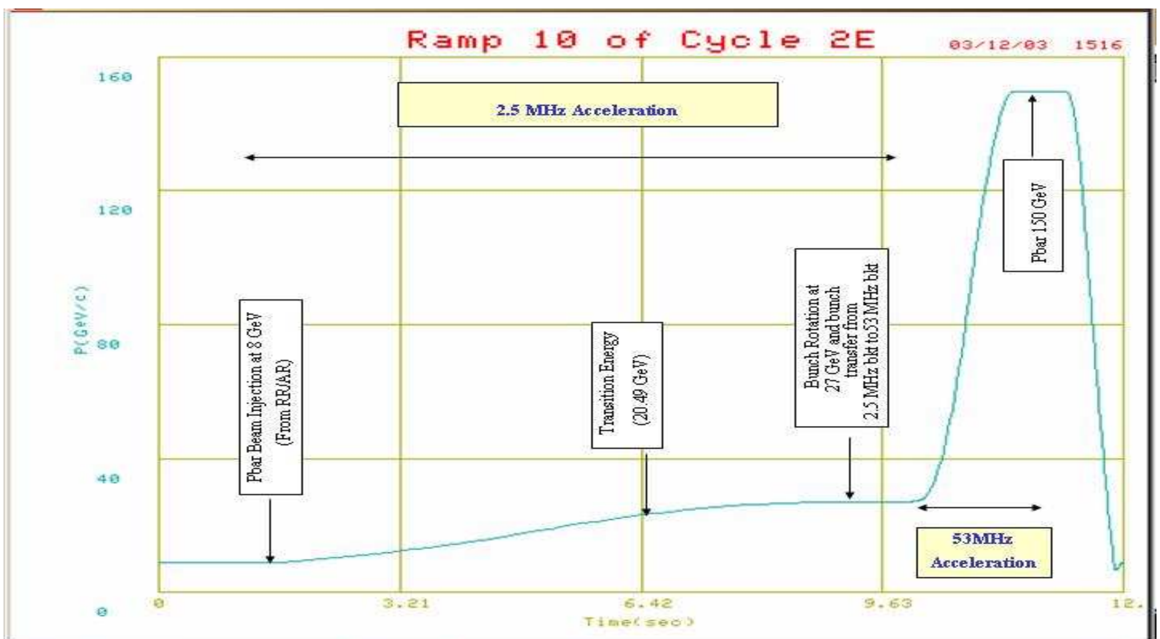

Figure 3. Pbar acceleration ramp "P (GeV/c)". From 8 GeV to 27 GeV the MI 2.5 MHz (h=28) rf system is be used for beam acceleration. For 27 GeV to 150 GeV we have used the MI 53 MHz (h=588) rf system. Various stages of acceleration are also indicated.

about 75 kV[7]. If we want to use the "standard" MI 150 GeV proton acceleration cycle (with $(dP/dt)_{max}$~220GeV/c/sec) here, we need much higher 2.5MHz rf voltage than 75 kV. Therefore, we have chosen a cycle with a $(dP/dt)_{max}$ ~3.2 GeV/c/sec during the acceleration from 8 GeV to 27 GeV, slightly past the MI transition energy ($\gamma_T \approx 21.836$). A 3 eVs beam bunch will have a $\Delta P/P$ about ±0.45% which is about 40% smaller than the momentum acceptance of the MI at transition energy (~±0.7%[7]). This nature of the 2.5 MHz acceleration allows us to accelerate beam bunches of longitudinal emittance of up to about 4 eVs without any beam loss through the transition energy.

The beam harmonic transfer from h=28 to h=588 takes place at 27 GeV front-porch after one or two sets of two quarter synchrotron bunch rotations in sequence. At the end of these bunch rotations the final bunch width will be considerably less than 18.9 nsec (the length of 53MHz bucket) and emittance will be preserved. The total time for this rf manipulation is about 0.15 sec. For example, a pbar bunch with initial longitudinal emittance of 1.5eVs is expected to have its bunch length after final rotation of about 9 nsec with half beam height $\Delta E_{1/2} \approx 110$ MeV. The required 53MHz rf voltage used to capture the beam is 0.85 MV with a total bucket area of 4 eVs and half bucket height ≈170 MeV. Here we assume the ratio of bucket area to bunch area ≈2.6.

Finally, these four bunches are accelerated to 150 GeV in 53 MHz rf buckets and transferred to the Tevatron. During the acceleration from 27 GeV to 150 GeV we use $(dP/dt)_{max}$ ~200 GeV/c/sec. The total MI cycle time is about 13 sec.

b) Beam Dynamics Simulations:

We have carried out beam dynamics simulations using a macro-particle Monte Carlo tracking code ESME[8]. Initially all simulations were carried out for 60E9pbars/bunch. We repeated these simulations with 170E9 pbars/bunch as the project goal changed[1, footnote on section 1]. Therefore, some simulation results shown here (figures 5, 6 and 7) are for 60E9 pbars/bunch and the rest are for 170E9pbars/bunch. The simulations are done for the following cases for the parameters listed in Table II:

1. No space charge effects
2. Including space charge effects and MI broad-band impedance
3. With and without beam-loading compensation on 2.5 MHz rf system and
4. With and without beam-loading compensation on 53 MHz rf system.

The simulations were also carried out to understand the effect of 53 MHz rf system during beam acceleration from 8 GeV to 27 GeV and during the rf-manipulations at 27 GeV. These simulation results and the operational lower limit on 53 MHz rf voltage (keeping the 53 MHz rf systems tuned to a required acceleration frequency) prompted us to pursue further simulations to keep 2.5 MHz rf voltage as high as possible during the bunch rotation. Thus we have three different simulation scenarios during the 27GeV h=28 to h=588 harmonic transfers, viz., i) iso-adiabatic ii) two quarter synchrotron rotations- one with Vrf(2.5 MHz)≈4 kV and next with Vrf(2.5 MHz)≈60 kV, iii) four

Table–II: The Main Injector machine parameters.

Parameters	
Mean Radius of the MI	528.3019 meters
Nominal γ_T	21.836
Beam Energy	8-150 GeV
Maximum RF voltage 2.5 MHz RF system (h=28) 5 MHz RF system (h=56) 53 MHz RF system (h=588)	 75 kV 15 kV 4 MV
Pbar bunch properties at injection: Longitudinal Emittance Bunch Intensity	 0.8-2.2 eVs/ 2.5 MHz bunch 50E9-170E9/bunch
For Space Charge Simulations: $Z_{\parallel}/n$ (broad-band) Average Beam pipe Radius α_1 – 2nd order term in the expansion of path length Average Beam radius Beam-pipe cut-off radius	 3.2Ω 5.08 cm 0.002091 5 mm 1.7GHz cut-off
Beam-loading compensation Simulations 2.5 MHz RF system (feed back) : Shunt Imp. and Q of the cavity resonance Effective reduction in shunt Imp. Effective reduction in Q of the cavities 53 MHz RF system (feed back): Shunt Imp. and Q of the cavity resonance Effective Reduction in shunt Imp. Effective reduction in Q of the cavities	 45kΩ and 112.5 Factor of 5.0 Factor of 5.0 520kΩ and 5000 Factor of 10.0 Factor of 10.0

quarter synchrotron rotations- one with Vrf(2.5 MHz)≈15 kV and next with Vrf(2.5 MHz)≈60 kV and repetition of the similar sequence of rf rotations. The details of the beam-dynamics simulation results presented here are explained in the refs. [4, 8-10] and summarized in this section. The simulation results shown here are for the last two scenarios and a schematic of bunch rotations for these two scenarios are depicted in figure 4A and B. The solid line represent the 2.5MHz rf voltage amplitude and the dashed line that for 53MHz rf voltage. The time is in relative units.

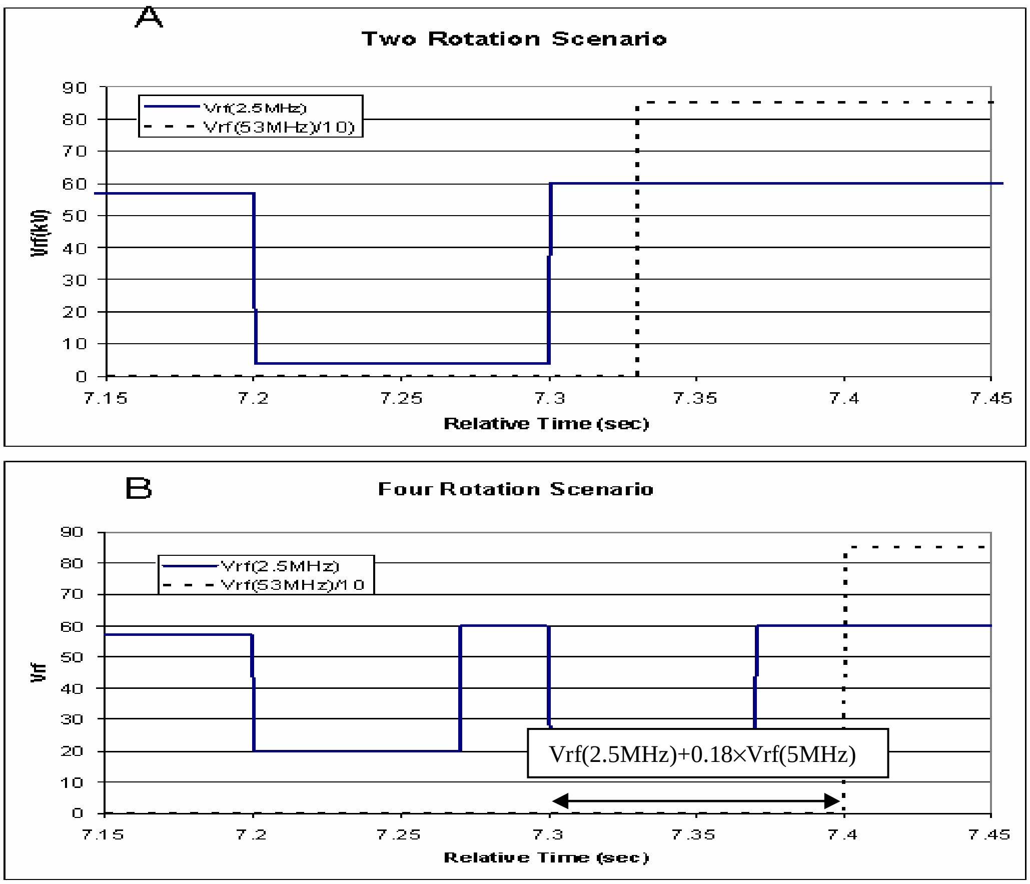

Figure 4. A schematic picture of 2.5MHz and 53MHz rf voltage curves at 27 GeV front porch for two and four rotation cases discussed here. Vrf are in units of kV.The 2.5MHz rf voltage is to the scale and 53MHz rf voltage is divided by 10. The time axis is in relative units.

Simulations without Space-Charge Effects: The 2.5 MHz pbar acceleration scheme is first simulated using the momentum ramp shown in figure 3 without including space-charge and without the beam-loading effects. The transition crossing in the MI is performed simply by jumping the rf acceleration phase from the +ve slope to –ve slope of the sinusoidal rf wave form. During this phase jump we see about 3% emittance growth for 1.5 eVs beam bunches. We do not see any further emittance growth throughout the acceleration cycle. The acceleration efficiency is 100%.

Effect of Space Charge and MI Beam pipe Impedance: The effect of beam space charge and couple impedance, $Z_{\parallel}/n$, between the beam particles and the beam pipe are

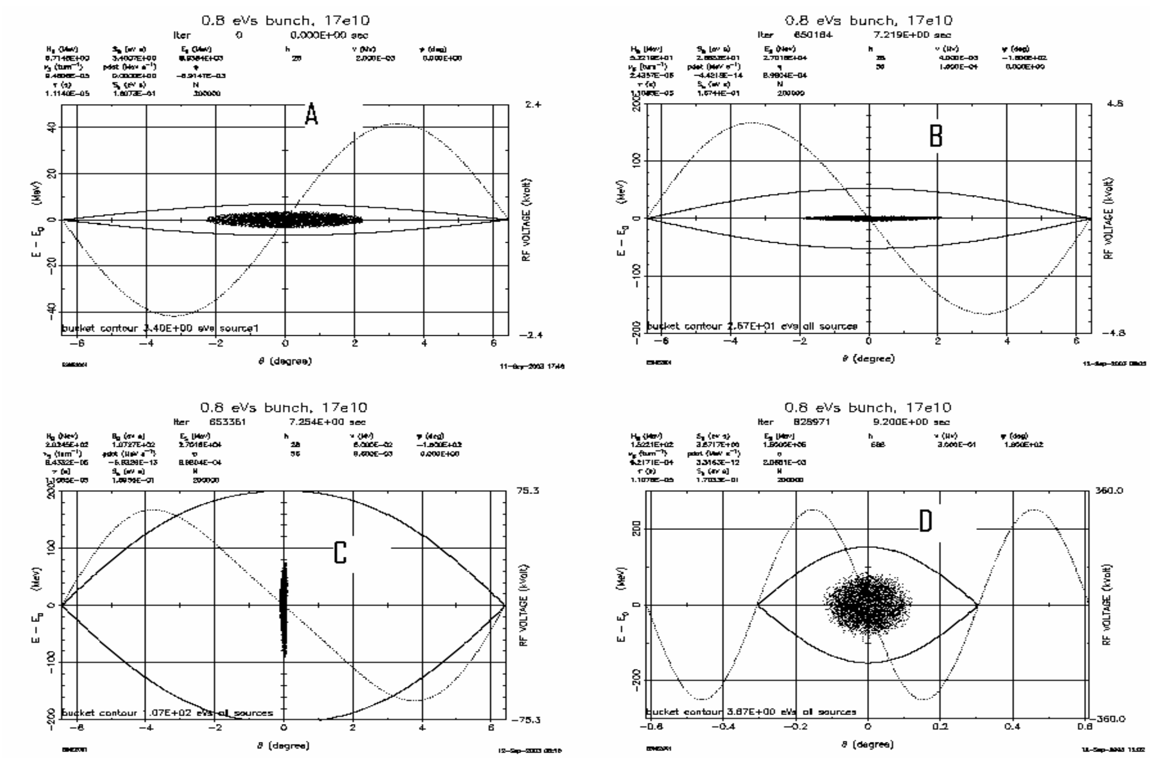

Figure 5. $(\Delta E,\Delta\theta)$-phase-space distribution of beam particles from ESME simulations of pbar acceleration from 8 GeV 150 GeV for ***170E9*** *pbars/bunch with longitudinal emittance of 0.8 eVs. The simulations are performed including space charge effects and shunt impedance of the MI. The closed contours represent rf bucket and the sinusoidal line show rf wave at A) injection in 2.5 MHz bucket, B) after first quarter synchrotron rotation at 27 GeV in a 4 kV 2.5 MHz rf bucket, C) after second, quarter synchrotron rotation at 27 GeV in a 60 kV 2.5 MHz rf bucket and D) at 150 GeV in 53 MHz bucket. Simulation predicts <6% emittance growth.*

simulated for a single bunch case. We have investigated the sensitivity of the 150 GeV longitudinal emittance as a function of $Z_{||}/n$. The space charge effect is known to be more destructive on low longitudinal emittance beam than on the large emittance beam bunches. Typical phase-space distributions at various stages of acceleration predicted from the simulations for an initial emittance of 0.8 eVs are shown in figure 5. In this case, we observe <10% emittance growths. The longitudinal emittance growth verse $Z_{||}/n$ for a 1.5 eVs beam bunch is shown in figure 6.

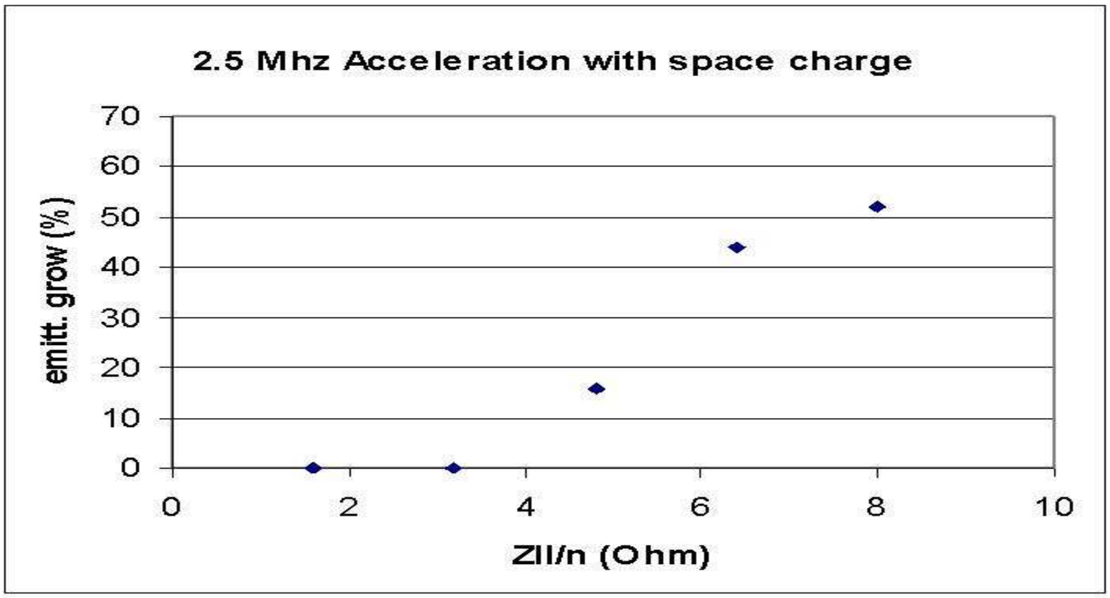

Figure 6. Longitudinal emittance growth as a function of Z/n of the Main Injector. The estimated Z/n for the MI is about 1.6Ω. For the most of our calculations we have used Z/n=3.2 Ω which gives a factor of two safety margin. The results shown here used the two rotation scenario and 60E9 pbars/bunch with an initial emittance of 1.5 eVs.

2.5 MHz Beam-loading Compensation: For simulations of the 2.5 MHz beam-loading, four bunches and a single cavity are modeled in the ESME code. The MI has five 2.5 MHz rf cavities in the ring. Therefore, we increased the shunt impedance of the cavity by a factor of five to correctly simulate the total beam loading voltage. We find that the simulations predict significant phase shifts which resulted in a considerable amount of emittance dilution as well as beam particle loss as shown in figure 7. Undesirable effect on the beam particle distribution even at 60E9/bunch due to beam loading effect is seen even in the early part of the acceleration cycle. It becomes rather severe during the bunch rotation. The peak beam loading voltage as a function of azimuthal angle around the MI ring is shown in figure 8.

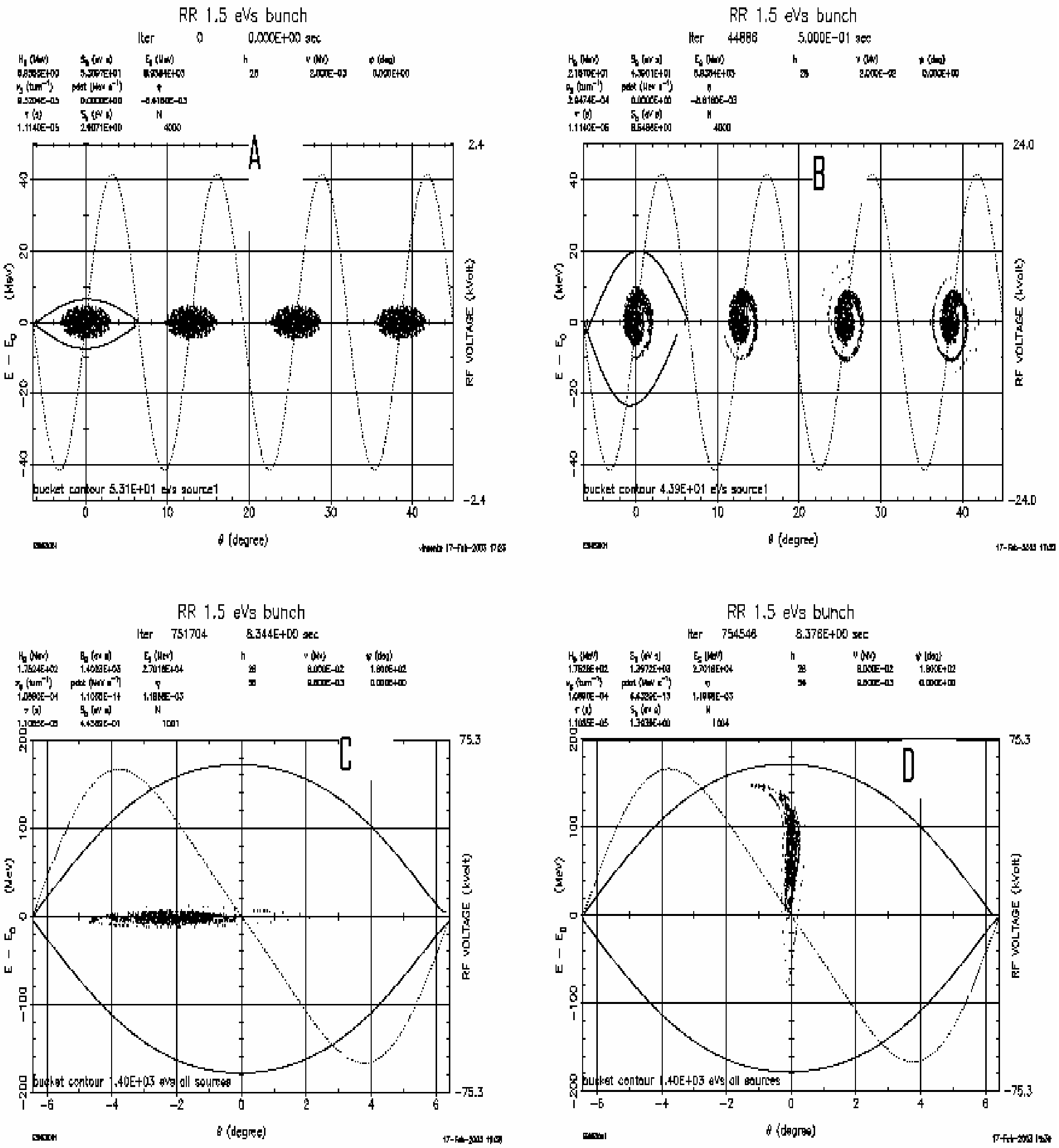

Figure 7. Phase space distribution of the beam particles from ESME simulations without any beam-loading compensation. A) Initial distribution at 8 GeV for four bunches, The longitudinal emittance was 1.5 eVs/bunch, B) distribution after 0.5 sec at 8 GeV, C)distribution of particles in the first bunch at 27 GeV and at the beginning of the 2nd rotation in 60 kV 2.5 MHz bucket and D)at the end of the 2nd rotation.

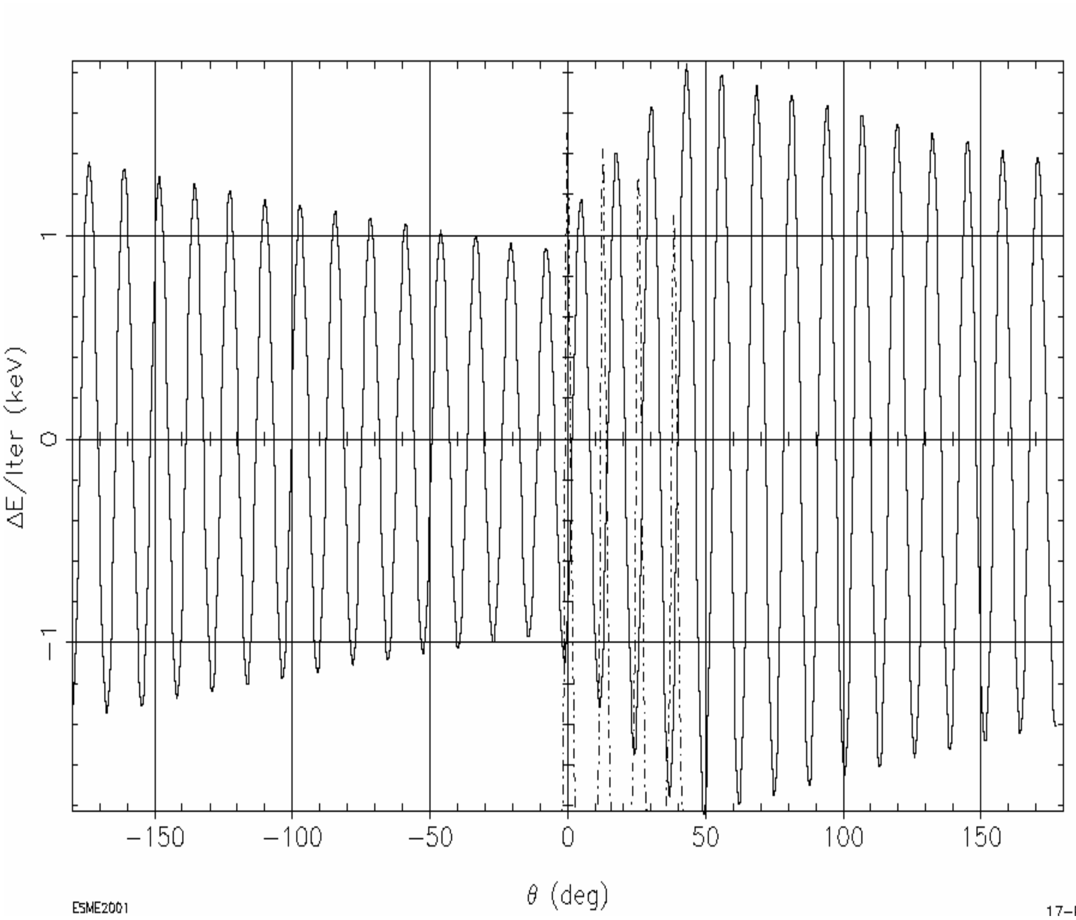

Figure 8. The 2.5 MHz cavity beam-loading voltage for the entire cycle. The peak voltage was about 1.9 kV per turn. The voltage will decay by about 50% in about 11μs (MIrev. Period). The vertical dashed lines indicate the position of the beam in the MI.

Recently, a feed-forward as well as a feed-back beam-loading compensation has been developed for the 2.5 MHz rf system [11] and implemented in the MI. The feed-back system is found to reduce the beam induced voltage by a factor of five and an effective reduction in charge by the feed-forward system is a factor of ten. We have modeled the beam-loading compensation in ESME.. The simulation results for 170E9 pbars per bunch and initial longitudinal emittance of 1.5 eVs are shown in figure 9. We find that the peak beam-loading under these circumstances to be about 0.22 kV and the minimum voltage to be less than 10 volts. The simulation results shown here indicate about 7% emittance dilution from 8 to 150 GeV.

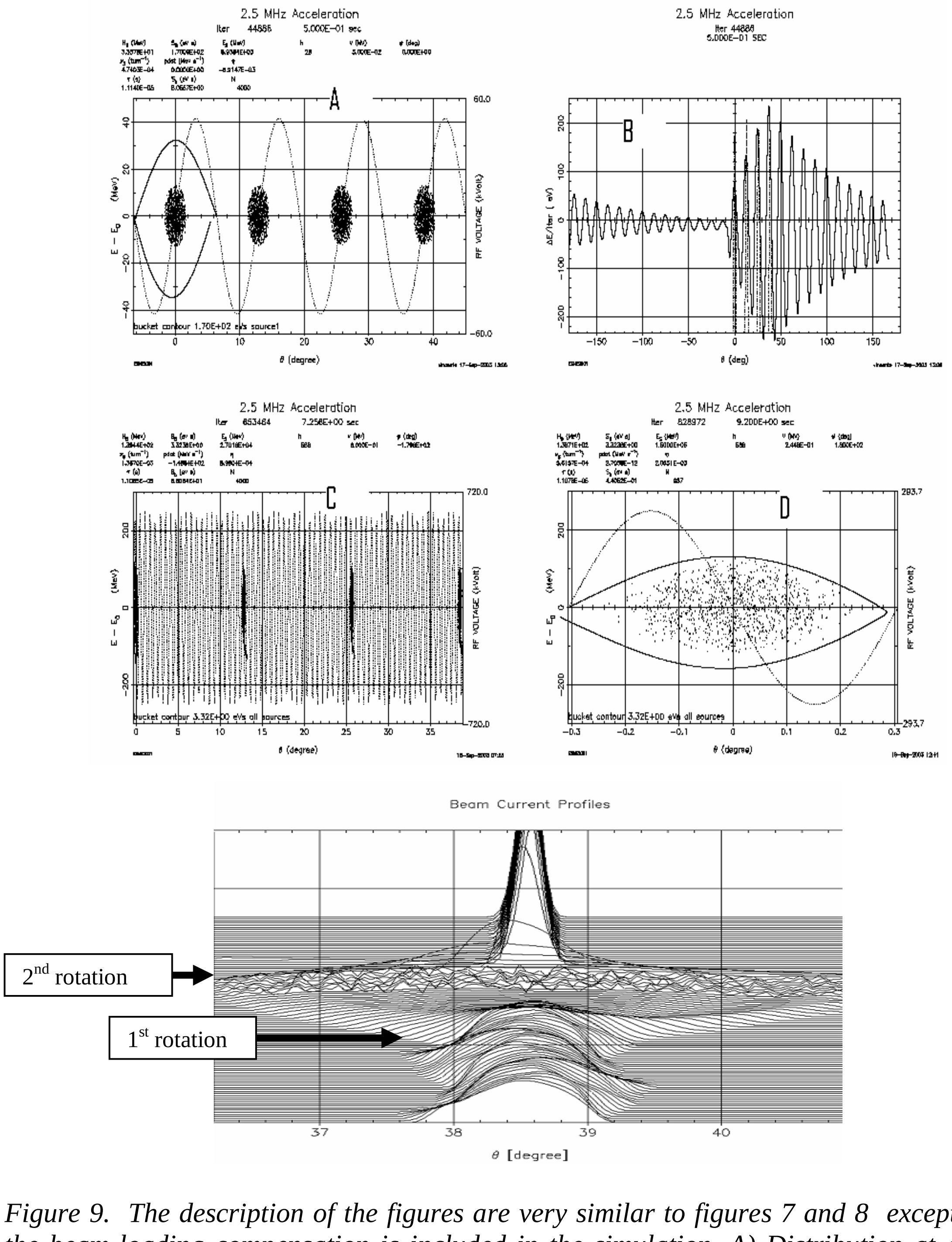

Figure 9. The description of the figures are very similar to figures 7 and 8 except that the beam-loading compensation is included in the simulation. A) Distribution at about 0.5 sec in the ring at 8 GeV. B)The corresponding beam voltage. C) Beam distributions of four bunches after rotation, D)First bunch in 53 MHz bucket at 150 GeV. The bottom figure shows predicted line-charge distribution as a function of azimuth angle from left to right and real time along the vertical direction during 1st and 2nd rotations. This represents predicted wall current monitor data. Initial long. emittance was 1.5eVs.

53 MHz Beam-loading Compensation: The shunt impedance and Q of a 53MHz cavity in the Main Injector are 520KΩ and Q = 5000, respectively[12]. Without 53MHz feed-back beam-loading compensation we expect an average beam induced cavity voltage of about 1kV/cavity/170E9pbars/bunch. The existing MI feed-back beam-loading compensation, which gives rise to a factor of ten lower effective shunt impedance and Q and, feed-forward beam loading compensation gives an effective charge reduced by a factor of ten[12], is what is modeled in our simulations. Figures 10A and 10B

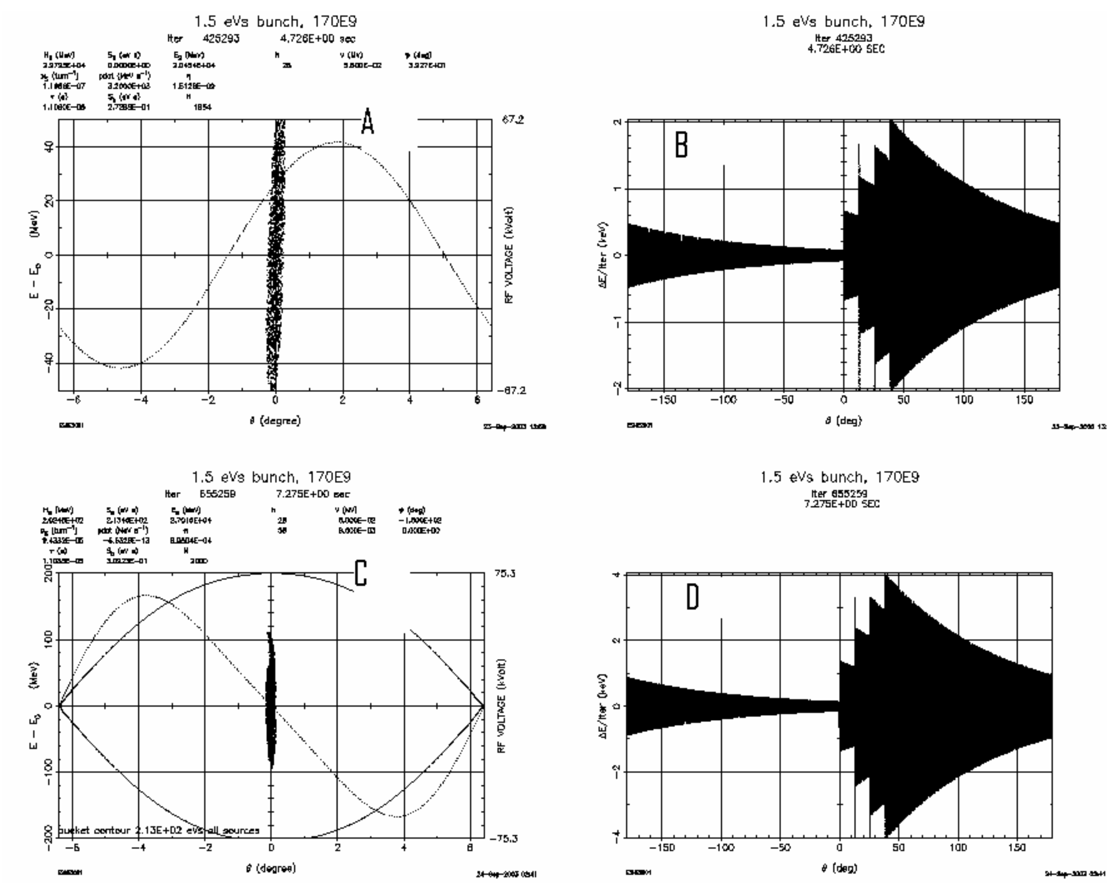

Figure 10A. Simulations for four bunch (170E9 pbars/bunch,1.5eVs/bunch) acceleration with 53 MHz beam loading compensation included. A) Phase space distribution for the first bunch just before the transition crossing (during the non-adiabatic time), when the bunches are quite narrow. B) the corresponding beam induced voltage and its decay in one revolution (max. $V_{induced}$≈2 kV). C)same at "A" but predicted distribution during the final phase of 4^{th} rotation and D)the corresponding beam induced voltage (max. $V_{induced}$ ≈4 kV).

show the results of simulations carried out for four bunches with 170E9 pbars/bunch and 1.5eVs/bunch. The beam loading voltages are expected maximum close to the transition crossing and just before 53MHz capture at 27 GeV. The average of emittance growth for four bunches during 8- 150 GeV acceleration is about 20% .

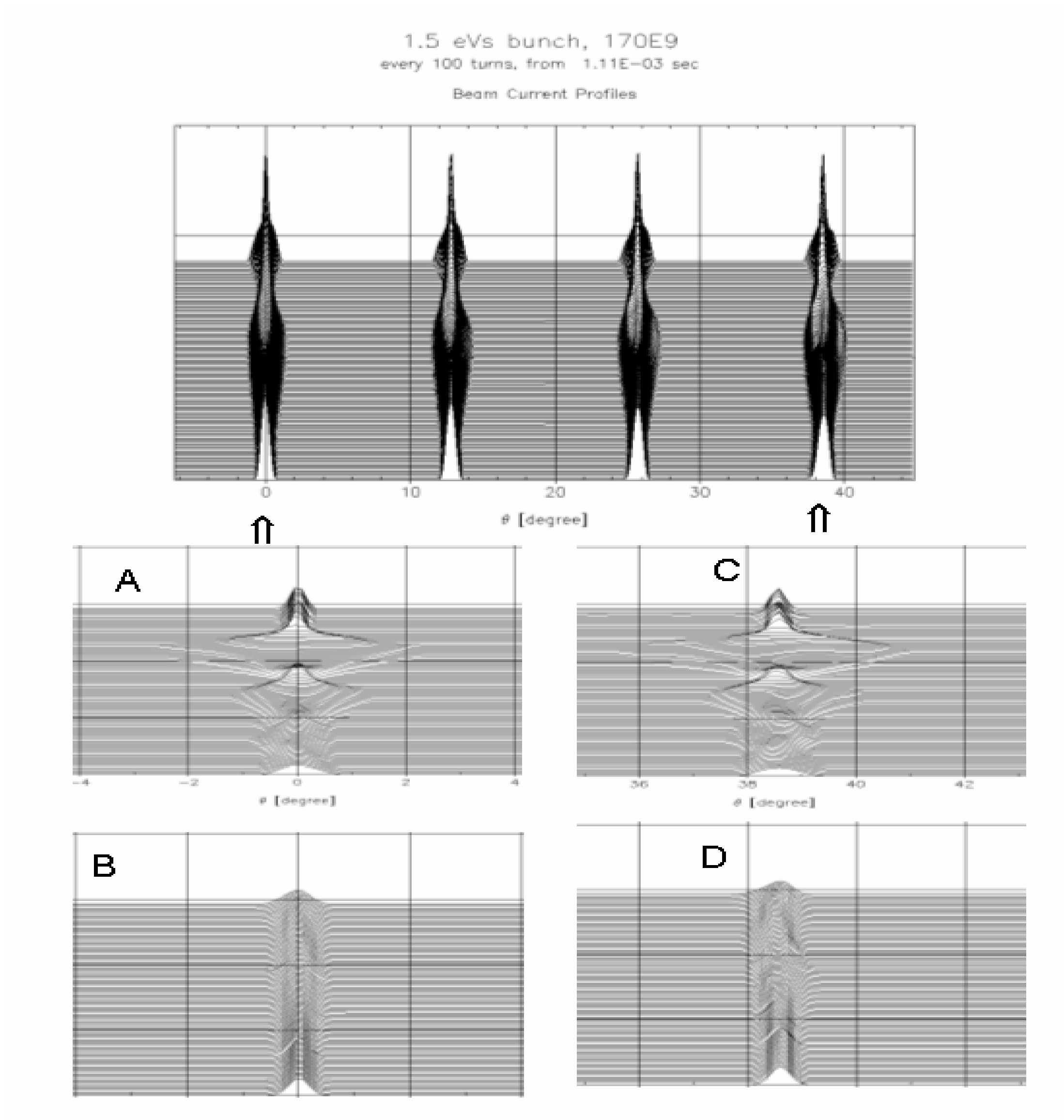

Figure 10B. Simulated charge current distribution. Top: all four bunches during the four rotations at 27 GeV. A and B: during rotation and transition crossing for the first bunch. C and D: similar results for the 4^{th} bunch. By close observation one sees a larger phase shift during transition crossing and bunch oscillations for the 4^{th} bunch as compared with 1^{st} bunch. At 150 GeV we see about 7% and 30% emittance growth respectively for these two bunches .

Effect of 53 MHz rf Voltage on the 2.5 MHz Acceleration: It is desirable not to short the MI 53 MHz rf systems during the 2.5 MHz acceleration from 8 GeV to 27 GeV. They need to be in tune with the MI magnet ramp so that at 27 GeV they can

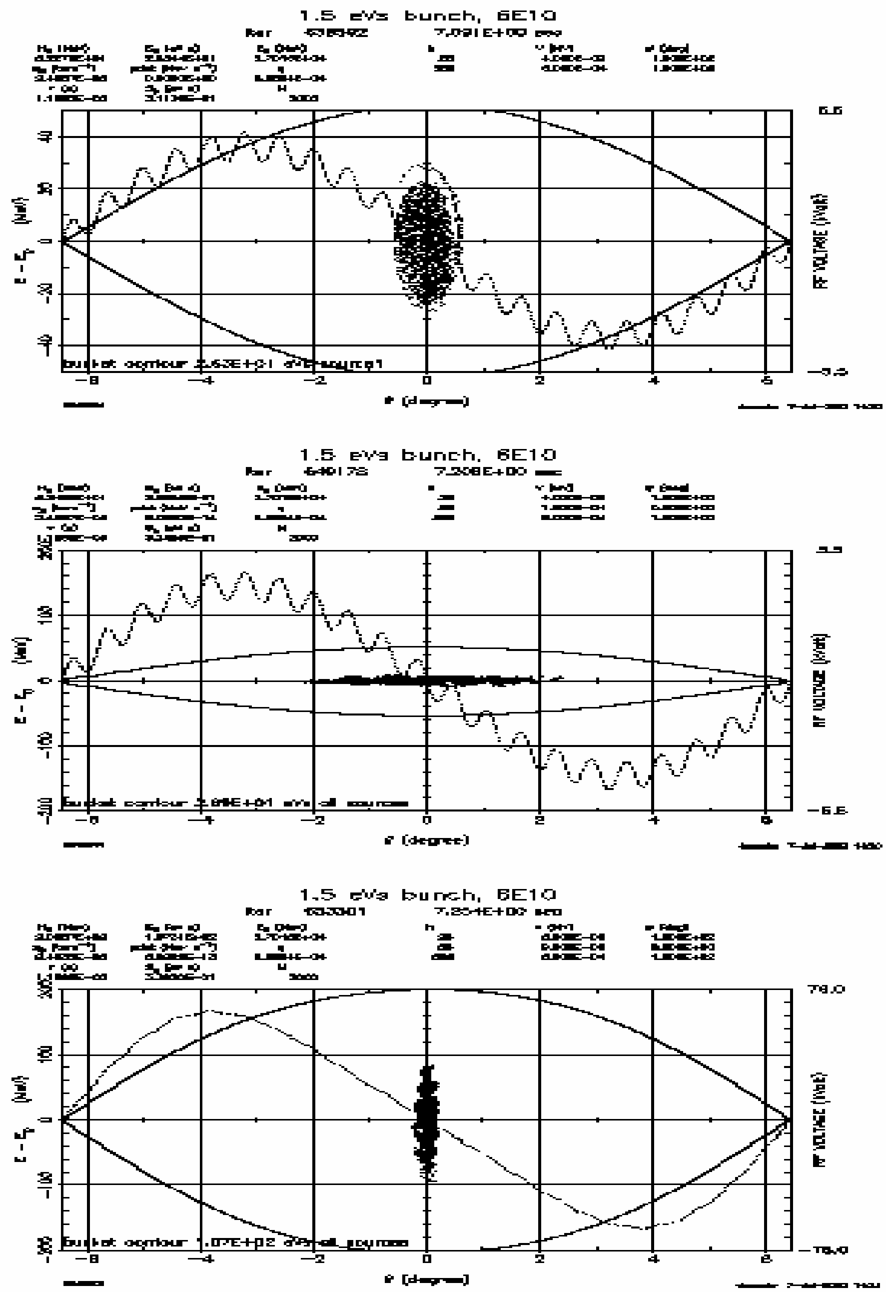

Figure 11. The effect of 53 MHz rf voltage on 2.5 MHz acceleration from 8 GeV to 27 GeV from ESME. Top: beam distribution before the first rotation in 4 kV 2.5 MHz rf bucket. Middle: After the first rotation. Bottom: After the second rotation in the 60 kV 2.5 MHz rf bucket. We assumed about 1 kV of 53 MHz rf voltage during these simulations.

be turned on smoothly so that the transfer of the pbars bunches to 53 MHz buckets is done with out any undesirable effects on the beam. We plan on keeping as low rf voltage on them as possible. However, the 53 MHz cavities have large impedances. Hence, the beam induced 53 MHz voltage and the power amplifier voltage affect the quality of the beam in 2.5 MHz buckets during the beam acceleration. To understand this effect we have carried out a series of simulations by superposing a small amount of 53 MHz rf wave on the 2.5 MHz rf accelerating voltage wave form. The results of such simulations are shown in figure 11. We find that the effect of 53 MHz component is very severe on

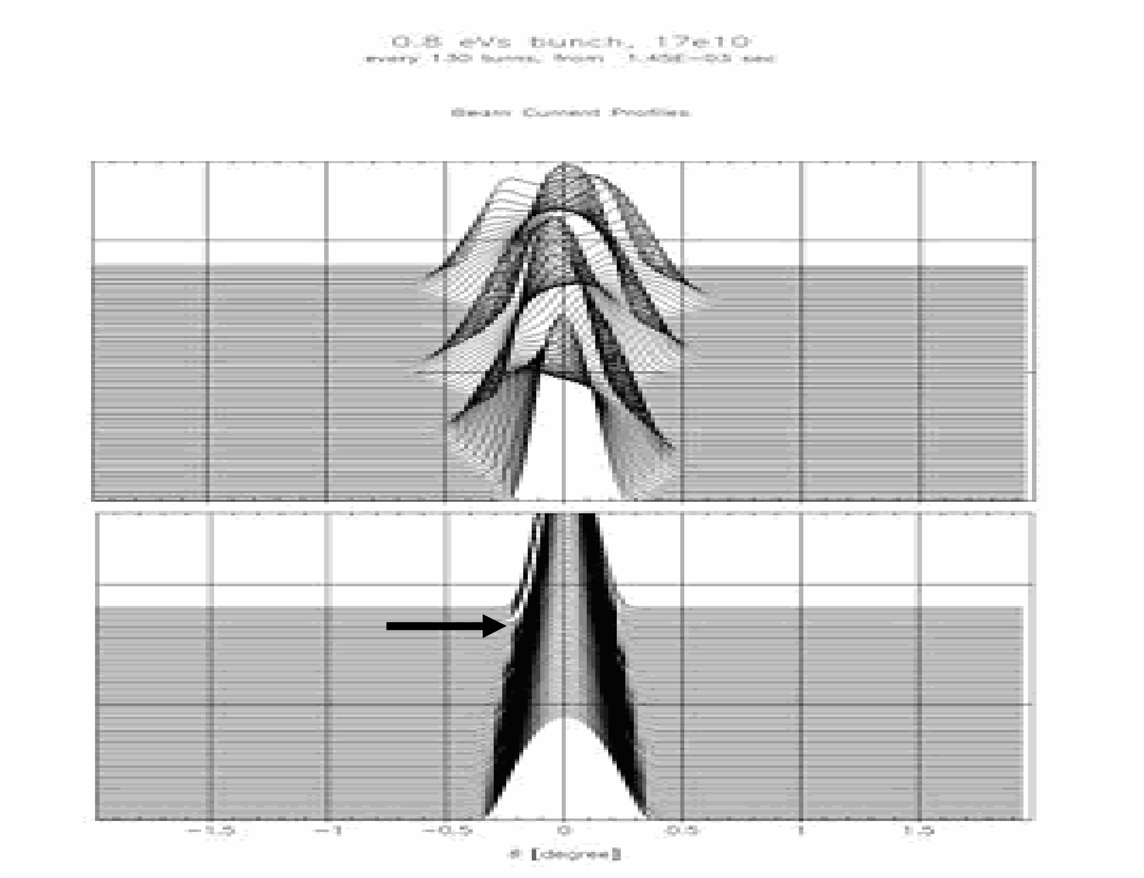

Figure 12. Charge density distribution as a function of azimuthal angle and time (vertical scale). The effect of 53 MHz rf voltage on 2.5 MHz acceleration during transition crossing on high intensity (170E9pbar/bunch) and low emittance beam (0.8 eVs). We assumed about 1 kV of 53 MHz rf voltage during these simulations. The arrow indicates the transition time.

low emittance beam during transition crossing and bunch rotation at low 2.5 MHz rf voltages. From our preliminary simulations we find that about 1 kV of 53 MHz would cause a factor of four emittance dilution on 0.8eV and 170E9 pbar/bunch from injection to beginning of 27 GeV acceleration. On the other hand we predict only about 40% dilution on 2.8 eVs beam bunches. From these studies we specify 53 MHz rf voltage to be less <400V (including 53 MHz beam-loading voltage) during the 2.5 MHz acceleration and bunch rotation.

<u>27GeV Bunch Rotations at Higher 2.5 MHz rf voltages:</u> The concerns detailed above demands that we keep 2.5MHz rf voltage as high as possible for the 8-27 GeV

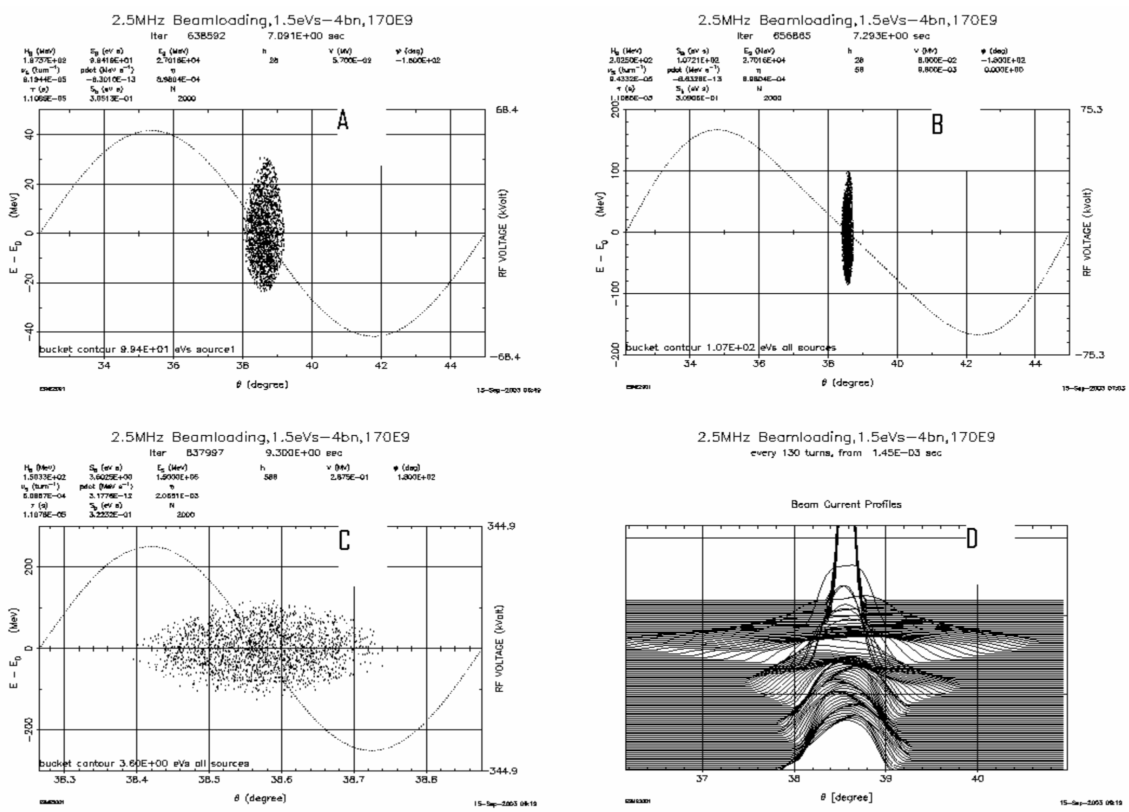

Figure 13. The ESME phase-space distributions for the 4th bunch for four rotation case These calculations were for initial emittance of 1.5 eVs. A) bunch in a 57 kV rf bucket at 27 GeV before first rotation starts B) At the end of the 2nd rotation C) beam in 53 MHz bucket before acceleration from 27 GeV to 150 GeV and D) the line-charge distribution as a function of time for the cases from A-C. The emittance growth from 8 to 150 GeV is predicted to be <10%.

acceleration and beam transfer to 53 MHz rf bucket. This can be met by performing two sets of bunch rotations in succession each comprising of a quarter rotation in about 15 kV 2.5 MHz rf voltage and next quarter rotation in about 60 kV rf voltage. A schematic diagram of such a case is shown in figure 4B. This reduces the effect of 53 MHz rf component by about a factor of four as compared with single rotation in a 60 kV bucket followed by a rotation in 4 kV 2.5 MHz rf bucket (see figure 4A). We have simulated the four rotation scenario for all cases explained earlier. Typical simulation results for four pbar bunches with 2.5 MHz feed-back and feed-forward beam-loading compensation for four rotation case is shown in figure 13. The total rf manipulation time at 27 GeV is about 0.2 sec which has negligible effect on overall 8-150 GeV cycle time.

Results of beam dynamics simulations discussed earlier are summarized in Table-III.

Conclusions from Simulations : Simulations suggest that to keep emittance growth less than 20% and no beam particle loss with this acceleration scheme we need feed-back and feed-forward 2.5 MHz and 53 MHz rf beam-loading compensations in place. We need a at least a factor of five reduction in the beam induced voltage through the feed-back beam loading compensation and an effective reduction in beam charge by a factor of ten from feed-forward compensation on 2.5 MHz rf system. For 53MHz rf system, at least a factor of five reduction in the beam induced voltage through the feed-back beam loading compensation and an effective reduction in beam charge by a factor of ten from feed-forward compensation are needed. There is already progress made towards these goals by HLRF group[11,12] for other MI project like slip stacking [13]. The 53 MHz rf voltage requirements during the 2.5 MHz acceleration and bunch rotation is <400V (the beam studies indicate we are not very far from this goal either).

Table–III: Results from beam dynamics simulations

Pbar Acceleration in MI with 2.5MHz (h=28) and 53MHz (h=588) RF Systems

ESME Simulation Results

Single Bunch, with Space Charge and Z/n

	Emittance (eVs)	rms emittances (eVs) 8 GeV	27 GeV	150 GeV	Growth(%)	beam loss	
2-rotation	0.8	0.16	0.17	0.17	6	0%	
	1.5	0.3	0.32	0.32	7	0%	
	2.8	0.54	0.6	0.57	6	5%	@
4-rotation	0.8	0.16	0.17	0.17	6	0%	
	1.5	0.3	0.32	0.32	7	0%	
	2.5	0.54	0.6	0.57	6	0%	

Four Bunch Acceleration:

Including 2.5MHz Beam-loading Compensation (with feed-back and feed-forward)

	Emittance (eVs)	8 GeV	27 GeV	150 GeV	Growth(%)	beam loss	
2-rotation	0.8	0.2	0.2	0.2	6	0%	
	1.5	0.3	0.3	0.3	4	0%	
	2.2	0.4	0.5	0.4	5	1.30%	@
4-rotation	0.8	0.16		0.17	6	0%	
	1.5	0.3		0.36	20	0%	
	2.8	0.54		0.64	19	5%	@

Including 53MHz Beam-loading Compensation (with feed back and feed-forward)

	Emittance (eVs)	8 GeV	27 GeV	150 GeV	Growth(%)	beam loss	
4-rotation	1.5	0.3	0.3	0.3	7	0%	#

@ These are not optimized. The work is in progress

\# for the 1st bunch

4. HLRF: Feasibility and Specifications

Four rf systems are used in this acceleration scheme - 2.5 MHz , 5 MHz, 53 MHz and 106 MHz rf systems. The rf specifications derived from the beam dynamics simulation results are given in Table IV. Some of the issues related to HLRF will be discussed here.

2.5 MHz and 5 MHz RF systems: The 2.5 MHz rf cavities are originally built for p and pbar coalescing at 150 GeV. But, the duration of 2.5 MHz acceleration is about 7 sec per pbar acceleration cycle. Therefore, the 2.5 MHz rf system feasibility study concerning the heating of the cavity was carried out by repeatedly exciting a cavity for 12 sec at a full voltage of 15 kV/cavity and letting it off for about 48 sec in a 60 sec cycle for several hours continuously[4]. We find that both voltage drooping and the frequency shifts are within the tolerable limits of 2.5 kV at 60 kV (total for five cavities) and frequency shift of 15 kHz.

During operation with this scheme there will be nine consecutive pbar transfers to the Tevatron; on each transfer the 2.5 MHz rf cavities will be on at full voltage only for about 7 sec. Hence, we do not expect cavity heating to be a concern. We have closely monitored cavity behavior during the beam studies conducted over the last several months and did not see noticeable effect of cavity heating up to about 60 cycles with a cycle gap of 120 sec and about 30 cycles with 60 sec cycle gap. We expect about 60 second as acceleration cycle time for pbars from Accumulator and about 120 sec for pbars from Recycler.

The 5 MHz rf system will be on only for about 100 ms during bunch rotation and this will not pose any problems.

53 MHz and 106 MHz rf systems: No problems are foreseen.

RF Cavity Beam-Loading Compensation Systems: Over the past couple years significant effort has been done on developing the MI rf beam-loading compensation system [11,12]. Some recent improvements are summarized below.

Presently 2.5 MHz Acceleration in the Main Injector uses fundamental feedback and feedforward up the ramp (FFUTR) on the 2.5 MHz and fundamental feedback on the 53 MHz. 53 MHz FFUTR was not used because of mixer bleed through problems when trying to paraphase the 53 MHz. Recently a new 49 MHz FFUTR system has been developed that should be available after the September 2003 shutdown. The 49 MHz FFUTR should aid the multi-batch transition for 2.5 MHz Acceleration because the bunch length of the beam is roughly 18 ns at this point. Also, a new scheme for doing the rotation after transition using 49 MHz fundamental feedback on the 53 MHz RF should soon be available. We have now been able to turn a 53 MHz station off with 49 MHz fundamental feedback and see 432 Volts at the gap per station. This equates to 7.7 kV for all 18 Stations when the stations are turned off. We should be able to get to half of that by raising the gain on the 49 MHz fundamental feedback by 6 dB. We believe that this will be ready about a month after shutdown.

Table IV. RF specifications at various stages of the acceleration in MI.

Approx. Cycle Time (sec)	P GeV/c	h=28 (2.5MHz system)	h=56 (5MHz system)	h=588 (53MHz system)	h=1176 (106MHz system)	Description
0 to .5	8.889	V=2kV for RR beam V=4.2k for AR Beam (Matching V(ARF4)=900V Phis=0deg	V=0.0kV	V= 0.0MV	V= 0.0kV	Injection of pbars. The 53 MHz rf system can be paraphase down to <0.4kV or turned off fron 8 GeV to 27 GeV
0.5 to 1.5	8.889	V=4-60kV Phis= 0deg	V=0.0 kV	V= 0.0MV phis=0	V= 0.0kV	Rise the V(2.5MHz) rf voltage adiabatically up to ~60 kV to shrink the bunches
1.5 to 5.5	8.889 to 20.5	V~60kV Phis ~45deg	V=0.0 kV	V= 0.0MV	V= 0.0kV	Acceleration up to transition energy of 20.5 GeV
5.5	~20.5	V~60kV Phis=45 to 135deg	V=0.0 kV	V= 0.0MV	V= 0.0kV	Cross transition Non-focusing time ~20 ms Jump the phasein ~1ms
5.5 to 8.7	20.5 to 27	V=60-1kV Phis~135deg	V=0.0 kV	V= 0.0MV	V= 0.0kV	Acceleration to 27 GeV
8.7-9.0	27	V=4-20kV Phis= 180deg	V=0.0 kV	V= 0.0MV	V= 0.0kV	Hold the beam for about 300ms (This time can be reduced to about 100ms)
9.0-9.03	27	V=60kV Phis= 180 deg	V=12kV Phis=0deg	V= 0.0MV	V= 0.0kV	Bunch Rotation in about 30ms
9.03	27	V=60kV Phis= 180 deg	V=12kV Phis=0deg	V=0.5MV Phis=180deg	V= 0.0kV	Beam capture in 53MHz rf bucket
9.04-10.04	27 to 150	V=0.0kV	V= 0.0kV	V=0.5- 3.5MV Phis~135deg	V= 0.0kV	Beam acceleration from 27GeV to 150 GeV
10.04-11	150	V=0.0kV	V= 0.0kV	V=0.5MV Phis~180deg	V= 0.0kV	Cogging bunches to Tevatron buckets

5. LLRF: The RF Control System for 2.5 MHz RF in the Main Injector

A 2.5 MHz RF control system is operational in the Main Injector and is designed to support a number of beam control processes. The focus of this review is the acceleration in 2.5 MHz buckets from 8 to 27 GeV. This acceleration cycle requires the following beam control functions:

- Beam transfer from the Booster and Accumulator
- Beam harmonic transfer from H588 to H28
- Bucket alignment between H588, H28 and H1 harmonics
- RF vector amplitude control for 2.5 MHz via curve generators and messages
- RF vector amplitude control for 53 MHz via A/B group counterphasing messages
- Feedforward acceleration phase angle real time calculation based on the MDAT distributed MI ramp momentum data
- 2.5 MHz acceleration and deceleration transition crossing based on RF frequency
- Beam detection and processing for 2.5 MHz Radial Position and a Frequency Phase Lock Loop (Fpll) via the VXI DSR module
- 2.5 MHz Beam Radial Position feedback via the ROFF curve and 2.5 MHz Fpll
- Beam harmonic transfer from H28 to H588

The control interface for 2.5 MHz is integrated into the I6 PA and MI LLRF front end by the addition of several high level messages and pop down datum. It inherits all of the previously existing command structure of the 53 MHz controller interface. The 2.5 MHz system is instrumented with several new detectors and monitoring points that are all available to ACNET and fast time plots at 720 Hz. These new instruments include beam phase, radial position, position error, frequency error and dozens more.

The present system fully supports all requests from the Main Injector department and is working well and reliably. The LLRF group has worked closely with the Main Injector department and will continue to do whatever it takes to fully support this project.

6. Beam Studies

This report gives a summary for the machine study results of the 2.5 MHz acceleration in the MI[14] before the September 2003 shutdown. All the data shown here are for proton beam and for two rotation cases with first rotation in a 4 kV and the second rotation in 60 kV 2.5 MHz stationary buckets (see figure 4A). The maximum bunch intensity was about 60E9protons/bunch. The 2.5 MHz feed back and feed-forward beam-loading compensation were on but feed-forward was not optimized. The 53 MHz feed back was on but not optimized for 2.5 MHz acceleration. The 53 MHz feed-forward compensation was off because it was not fully commissioned.

The acceleration scheme is similar for proton and pbar beam bunches. With the proton beam, we first produce four 2.5 MHz bunches at 8 GeV to mimic the beam arising from the Recycler (which can produce only the 2.5 MHz bunches) or beam from the Accumulator. Details of such procedure is explained elsewhere [15].

The studies were conducted on a dedicated MI-cycle $20. Since the full 2.5 MHz acceleration cycle shown in figure 3 consumes a significant portion of the standard 60 sec long pbar stacking time-line, these studies were proposed in stages viz.,

1. Acceleration from 8 GeV to 27 GeV until the bunches are captured in 53 MHz buckets where in the 2.5 MHz proton bunches are prepared at 8 GeV (cycle time ≈10 sec).
2. Acceleration from 27 GeV to 150 GeV where in the 2.5 MHz bunches are prepared at 27 GeV (cycle time < 1.5 sec).
3. Combine the steps 1 and 2.
4. Finally, accelerate the pbars.

The beam studies explained here mainly emphasizes the first two steps. The steps 3 and 4 are quite straight-forward and we will pursue them after the September 2003 shutdown. A detailed description of the study results are given in Reference [14].

From 8 to 27 GeV acceleration and at beam harmonic transfer from h=28 to h=588, the 53 MHz rf voltage was kept as low as possible (<1 kV) by paraphrasing group-A and group-B of 53 MHz rf cavities. (see cyan traces in figures 15 and 18). The algebraic sum of the rf voltages was just above the multi-pactoring limit of about 500 kV (on I3 console application page) which helped us to bring the 53 MHz rf voltage very smoothly from <1 kV to 550 kV in a matter of a few mili-seconds at the time of harmonic transfer.

a. Beam Acceleration Status:

By the first week of July 2003, we were able to establish the 2.5 MHz RPOS closed loop (figure 20) operation and phase feed-back. These were major steps in LLRF. Several LLRF diagnostic tools have been developed to monitor feed back controls. All the 2.5 MHz acceleration in the MI prior to this time were done open-loop. All acceleration studies presented here were carried out using RPOS loop closed and phase-feed back loops. Now, we routinely accelerate four 2.5 MHz bunches of beam from 8 GeV to 27 GeV with 100% transmission efficiency (see figures 15 and 18).

Throughout the course of our study, the transverse emittance is often measured at various times up the ramp. We do not see any transverse emittance growth throughout the 2.5MHz acceleration from 8 to 27GeV. Typical flying wire data showing the measured transverse emittances for horizontal and vertical planes are shown in figure 14. The figure on left for 8 GeV, and the figure on right for 27 GeV, are taken on two different acceleration cycles. We did not see any emittance dilution within the measurement errors.

The single-bunch and four-bunch acceleration phenomenon have been studied separately. The figures 15-17 show data from the single-bunch acceleration. The bunch intensity used for this study was ≈60E9 and the beam loading effect was expected to be minimum for single bunch acceleration case. This study also demonstrated single bunch acceleration capability of the newly developed 2.5 MHz LLRF.

The data shown in figure 16 is a sample for single bunch crossing transition energy. During this data-taking the RPOS loop was not optimized. For this case we found beam emittance dilution from 8 to 27 GeV before bunch rotation was <25%.

The data on figure 17 shows the bunch rotation in 2.5 MHz rf buckets (first rotation in 4 kV and 2^{nd} rotation in 60 kV buckets and the final capture in 53 MHz buckets. Within the measurement error we do not see any emittance growth.

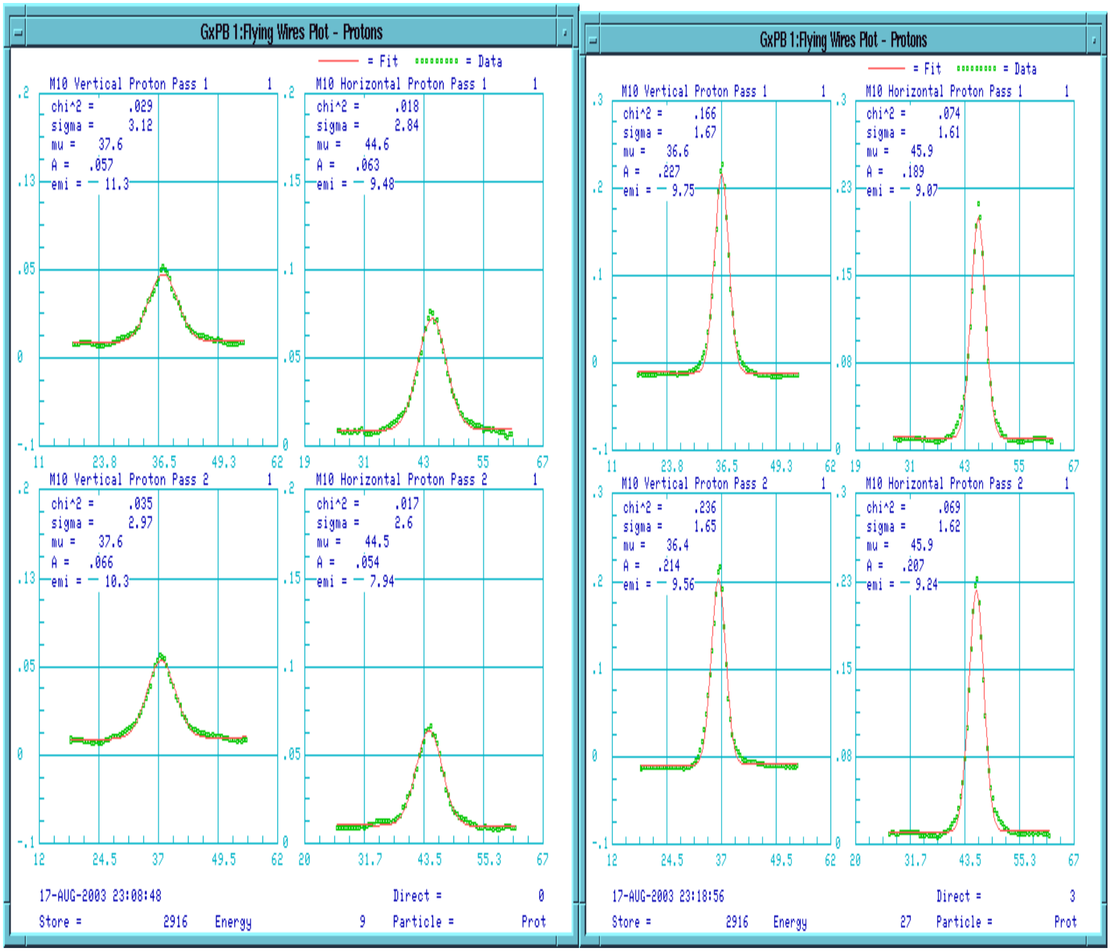

Figure 14. Flying wire data used to measure the transverse emittance of the beam at 8 (left) and 27 GeV(right). We do not see any emittance growths within the measurement errors. The data on the top correspond to the first pass and the those on the bottom are for second pass. The measurement errors in horizontal plane was about 15%, in vertical plane the error was <20%

Next three figures are for one Bunch Acceleration Data

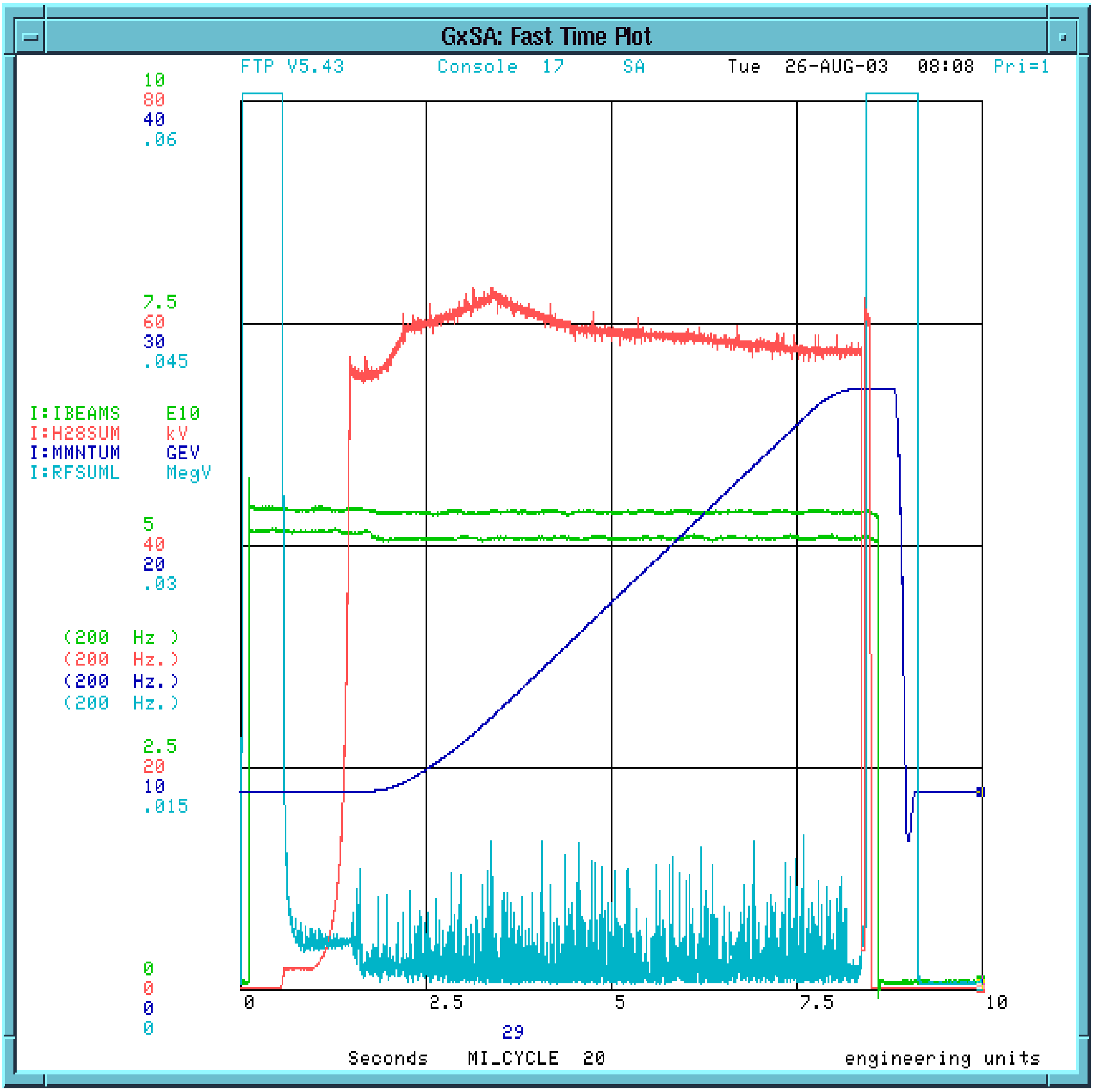

Figure 15. One bunch acceleration. Green trace: beam intensity, blue trace: MI magnet ramp, cyan: 53 MHz rf voltage maximum amplitude, and red trace: 2.5 MHz rf voltage amplitude. The magnet ramp had a 0.5 sec long front porch at 27 GeV.

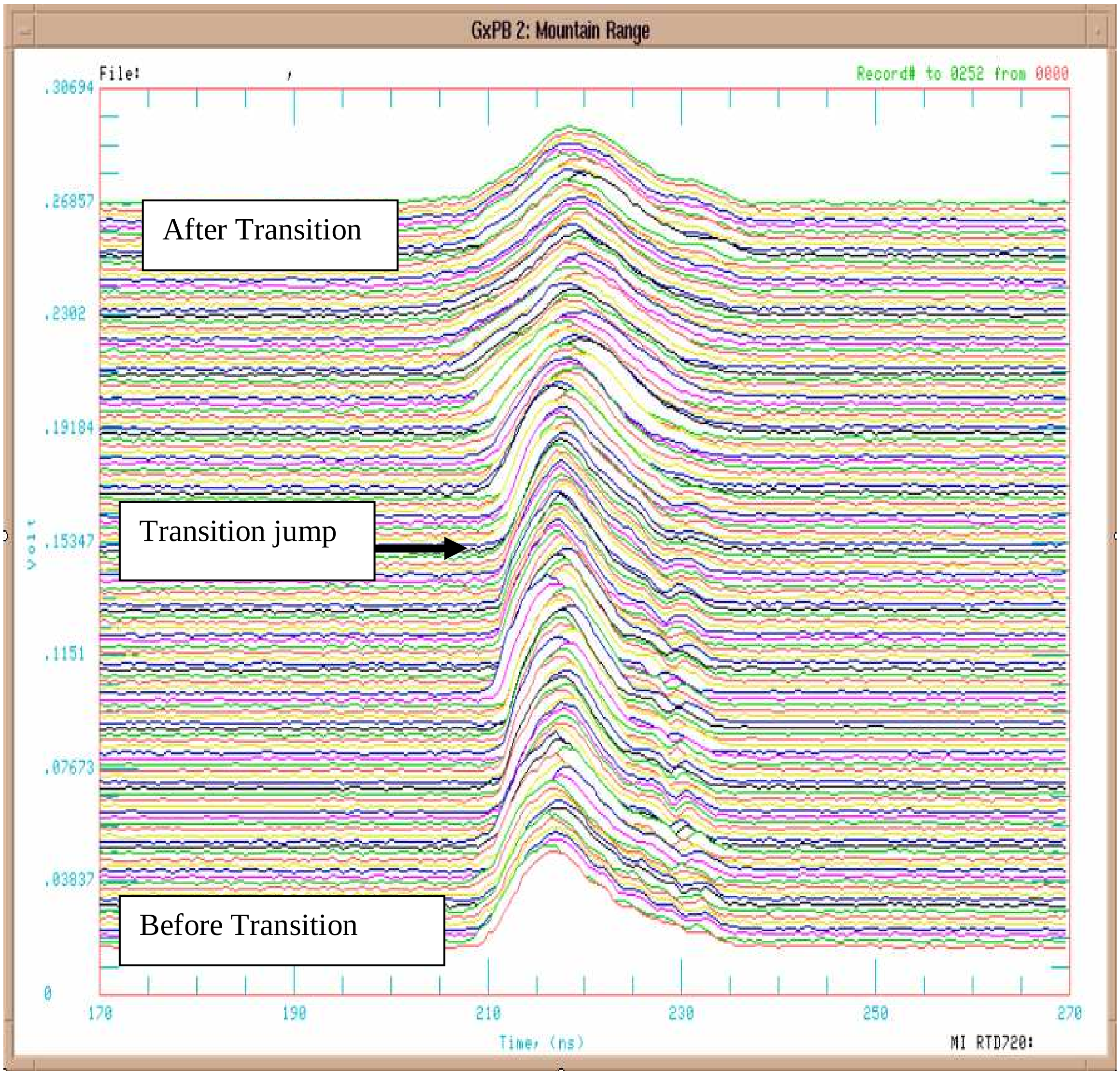

Figure 16. Wall Current Monitor data taken for one bunch acceleration during transition crossing. The arrow indicates approximate location of phase transition region. The acceleration time is along the vertical axis. The data shown is for about 0.7 sec. A small distortion of the bunch before transition is seen on this data because of 2.5MHz phase mis-alignment at 8 GeV. This will to be corrected during the operation.

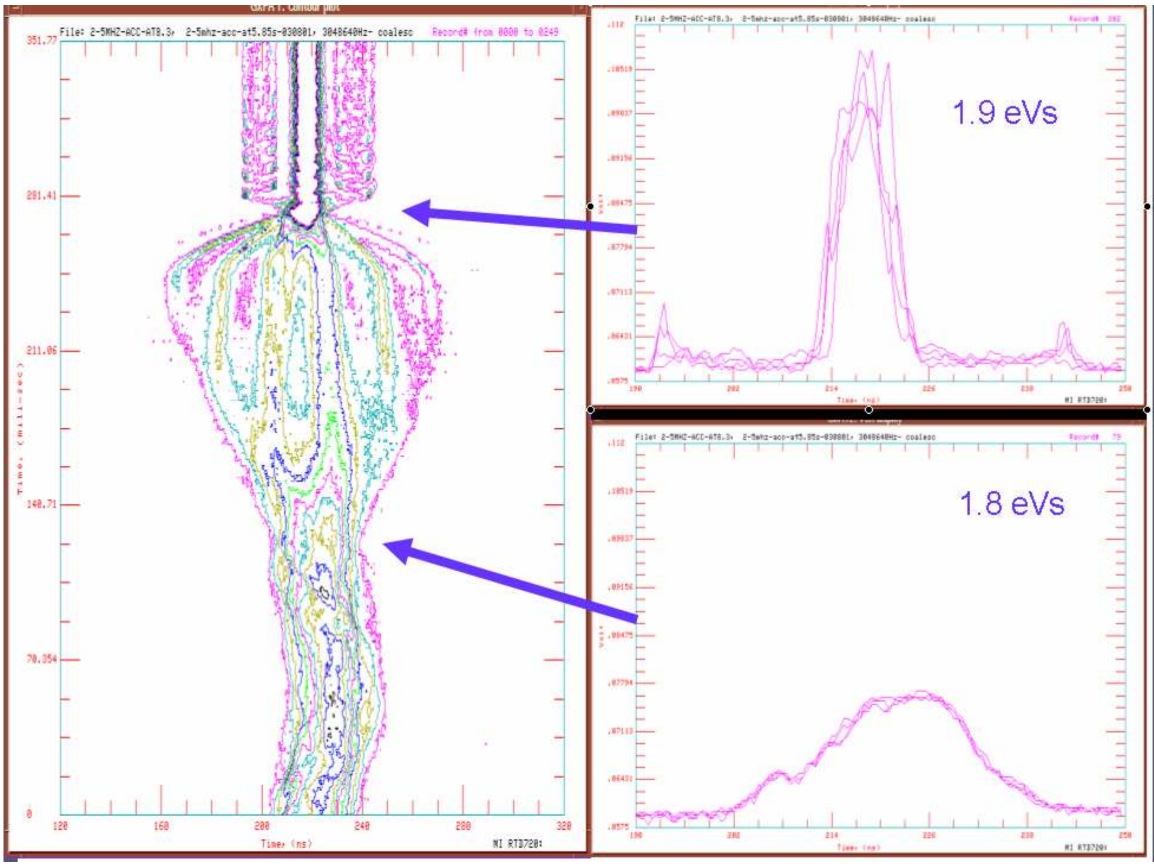

Figure 17. Wall Current Monitor data, contour plot (left) and individual bunch displays(right) taken for one bunch acceleration during before rotation and after capture in 53 MHz bucket, respectively. On the contour plot the real time is along the vertical axis. The horizontal axis represents azimuthal coordinates of the beam relative to MI AA marker.

The data shown in figures 18-25 illustrate typical results from four bunch acceleration beam studies. Before data taking we tuned the injection, transition crossing and harmonic transfer at 27 GeV for 60E9, and longitudinal emittance ≈ 1.8 eVs. The final settings for transition crossing and harmonic transfer were quite different from that of single bunch case. The acceleration efficiency for 4-bunch acceleration is shown in figure 18.

The mountain range picture of the four bunch ~60E9 protons/bunch case at 8 GeV bunch compression, just before the beginning of the acceleration, is shown in figure 19. We do not see any emittance growth during the bunch compression at 8 GeV.

The data taken during RPOS loop tuning is shown on figure 20. We find that there is more than ±5mm acceptance during transition crossing for 2.5 MHz acceleration.

Figure 21 shows data for four-bunch transition crossing. For these studies the transition crossing was tuned optimizing performance of the 2nd bunch. The 53 MHz feed-forward beam-loading compensation was not on and 2.5 MHz beam-loading compensation was not optimized. Obviously the bunch # 2 and bunch #4 were making very much different phase jumps as seen in figures 22 and 23. Thus we see clear beam loading effects on transition crossing.

Rest of the beam data are for four-Bunch Acceleration

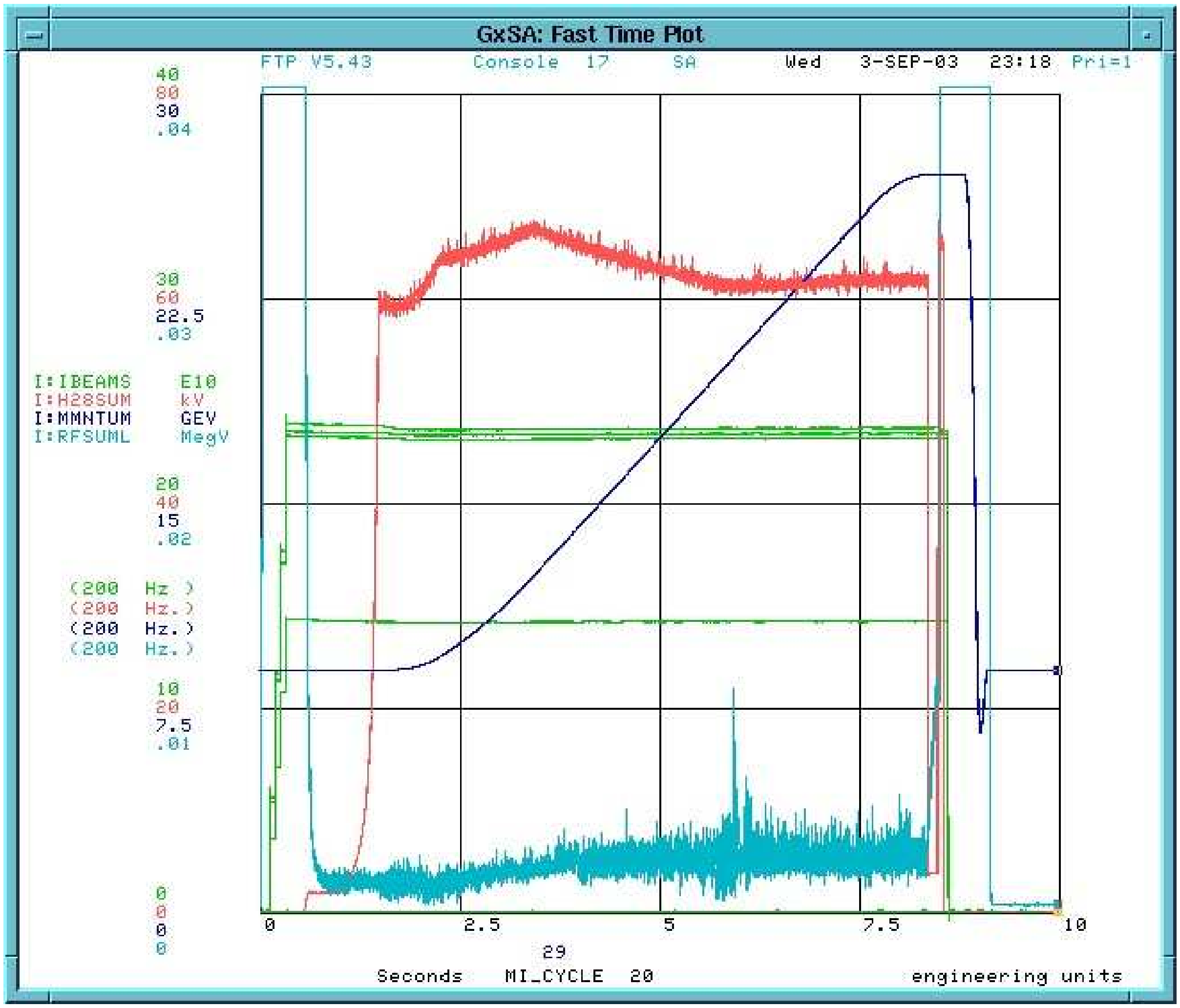

Figure 18. Four- bunch acceleration. For details see caption for figure 15 and the text.

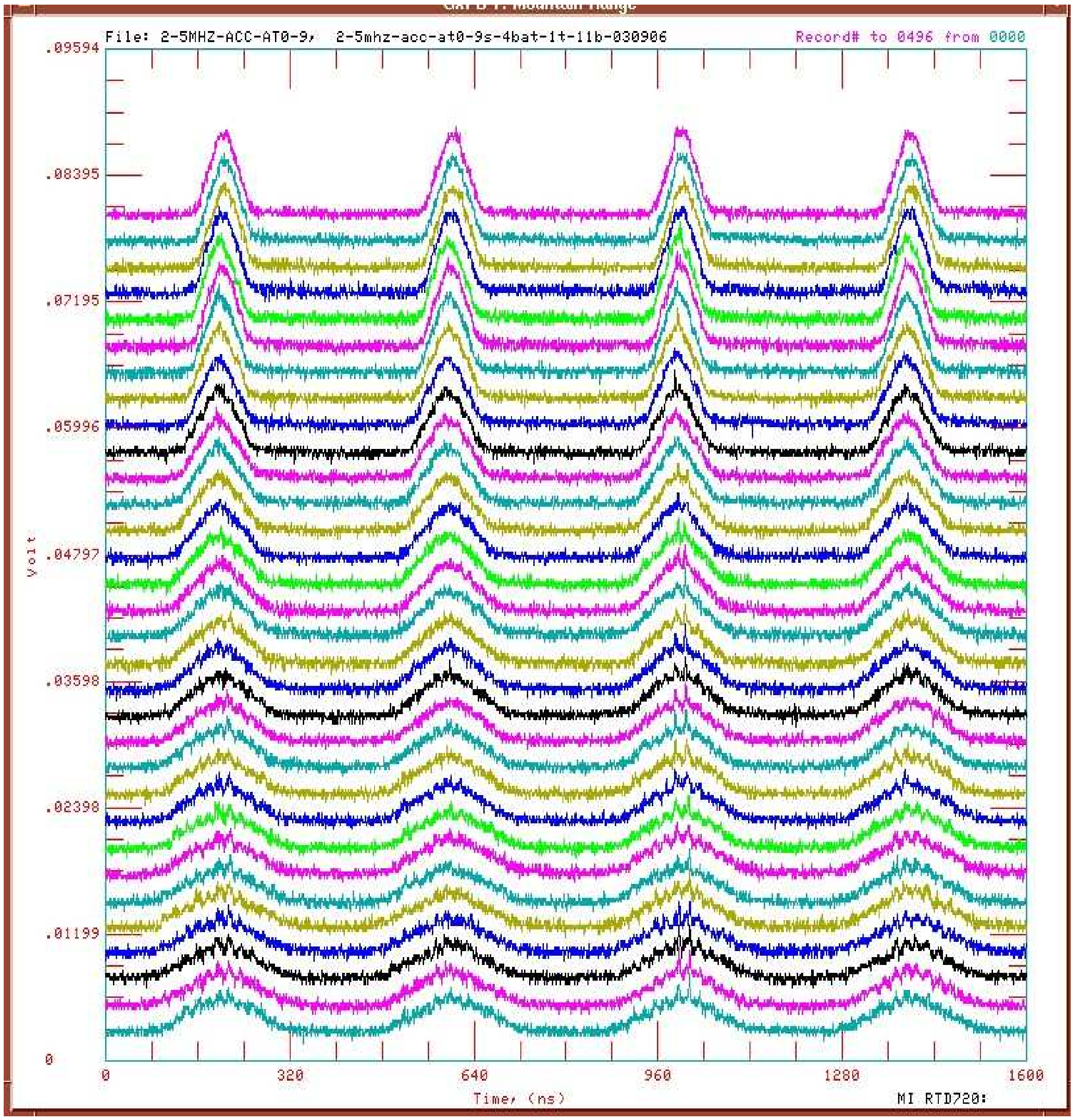

Figure 19. WCM data for four bunch at 8 GeV. Lower most trace represents the beam profile at 8 GeV in 2.5 MHz bucket with 2 kV amplitude. The top-most trace shows the bunches at the beginning of 2.5 MHz acceleration, i.e., in 50 kV rf bucket. The average longitudinal emittance of four bunches was about 1.84eVs (±20%)

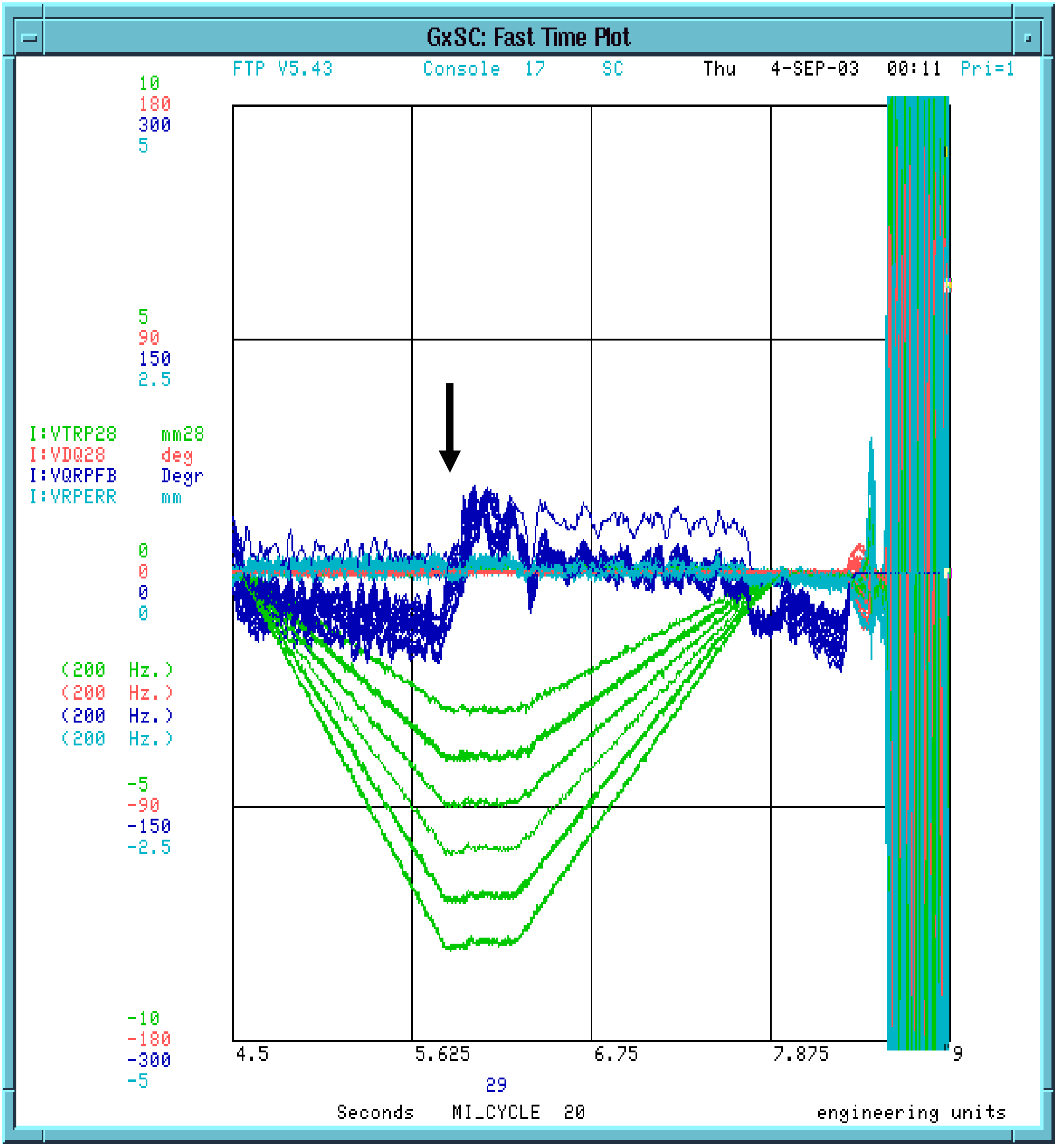

Figure 20. LLRF devices used for beam acceleration control and diagnostics. Green and cyan traces: 2.5 MHz RPOS signal and error signals. Remaining two curves show the relative phase information. The data show beam behavior around transition energy. The arrow shows an approximate transition crossing time.

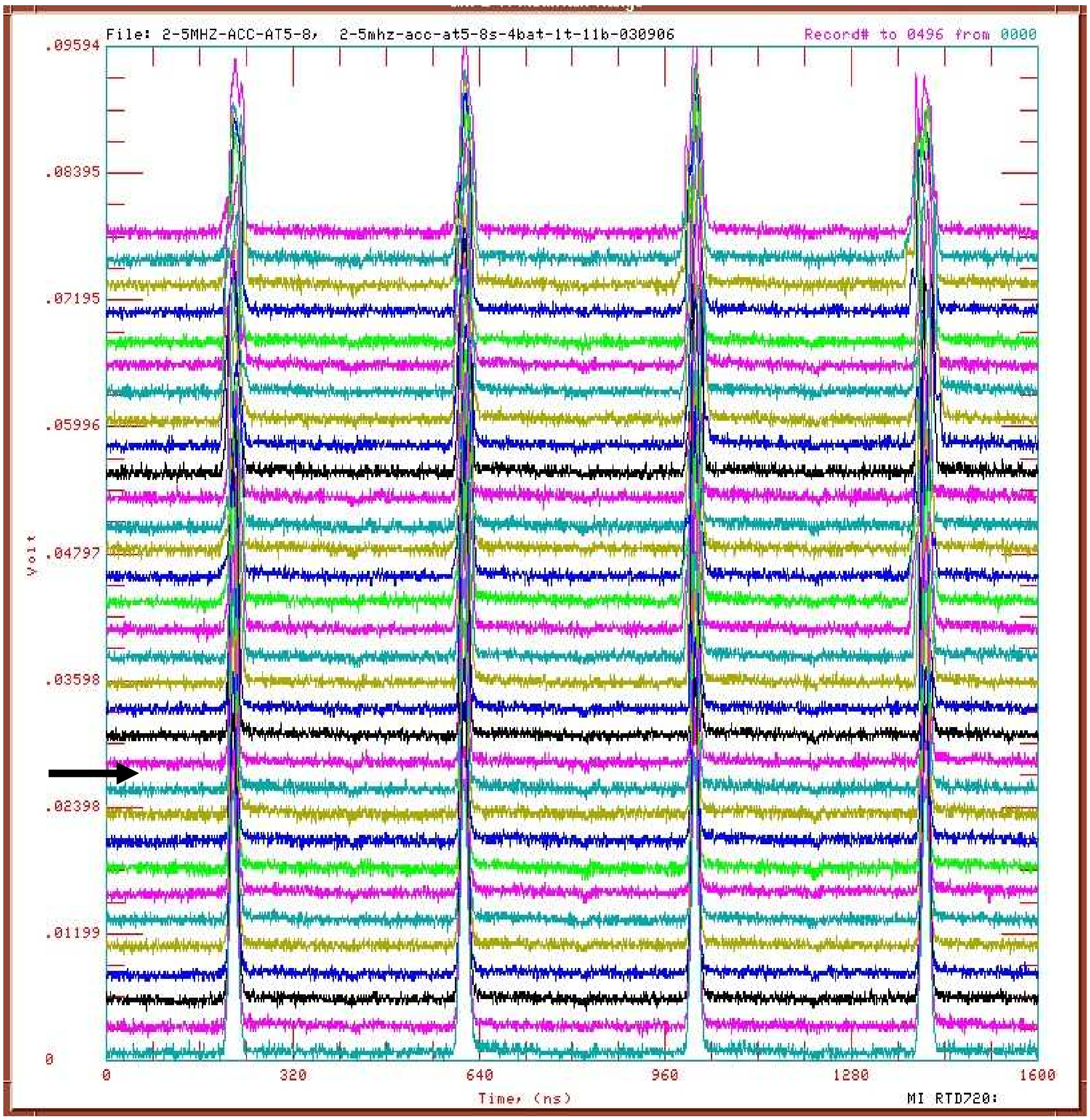

Figure 21. WCM data for four bunches during transition crossing. The expanded 2nd and 4th bunches are shown in later figures.

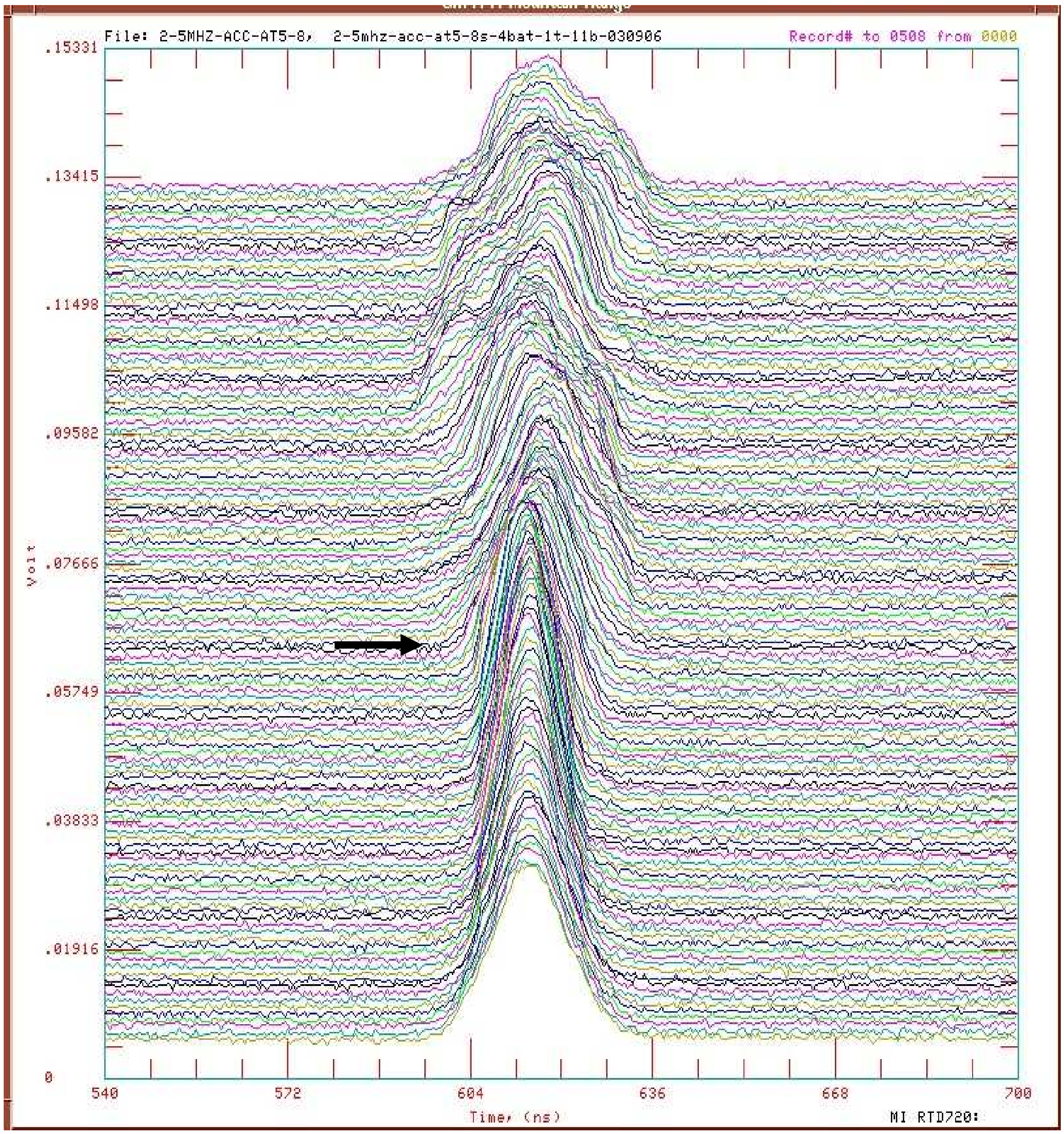

Figure 22. WCM data for the 2nd bunch of the four bunch acceleration around the transition crossing. The arrow shows approximate timing for the transition phase jump. This shows data for about 0.77 sec. The bunch length around transition is about 20 nsec.

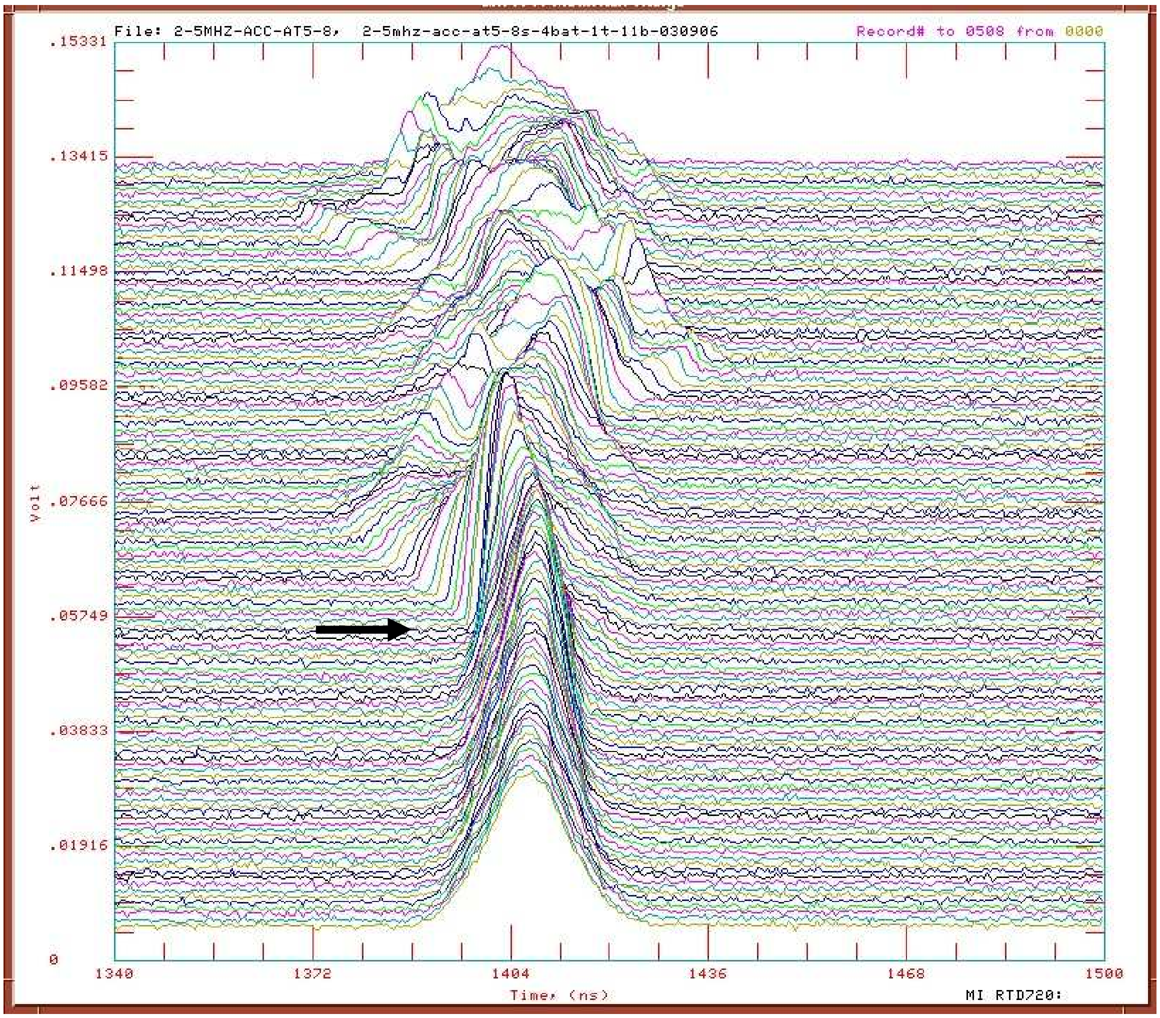

Figure 23. WCM data for the 4th bunch of four bunch acceleration around the transition crossing. The arrow shows approximate timing for the transition phase jump.

The data corresponding to the two bunch rotations at 27 GeV are shown in figure 24 (wall current monitor data) and 25 (contour plots of the same). These also show clear difference between 2nd and 4th bunch during the rotation and 53 MHz final capture.

We have extracted the longitudinal emittance at various phases of the acceleration. The method of analysis and the results on the data taken just before the September 2003 shut-down are explained in the next section.

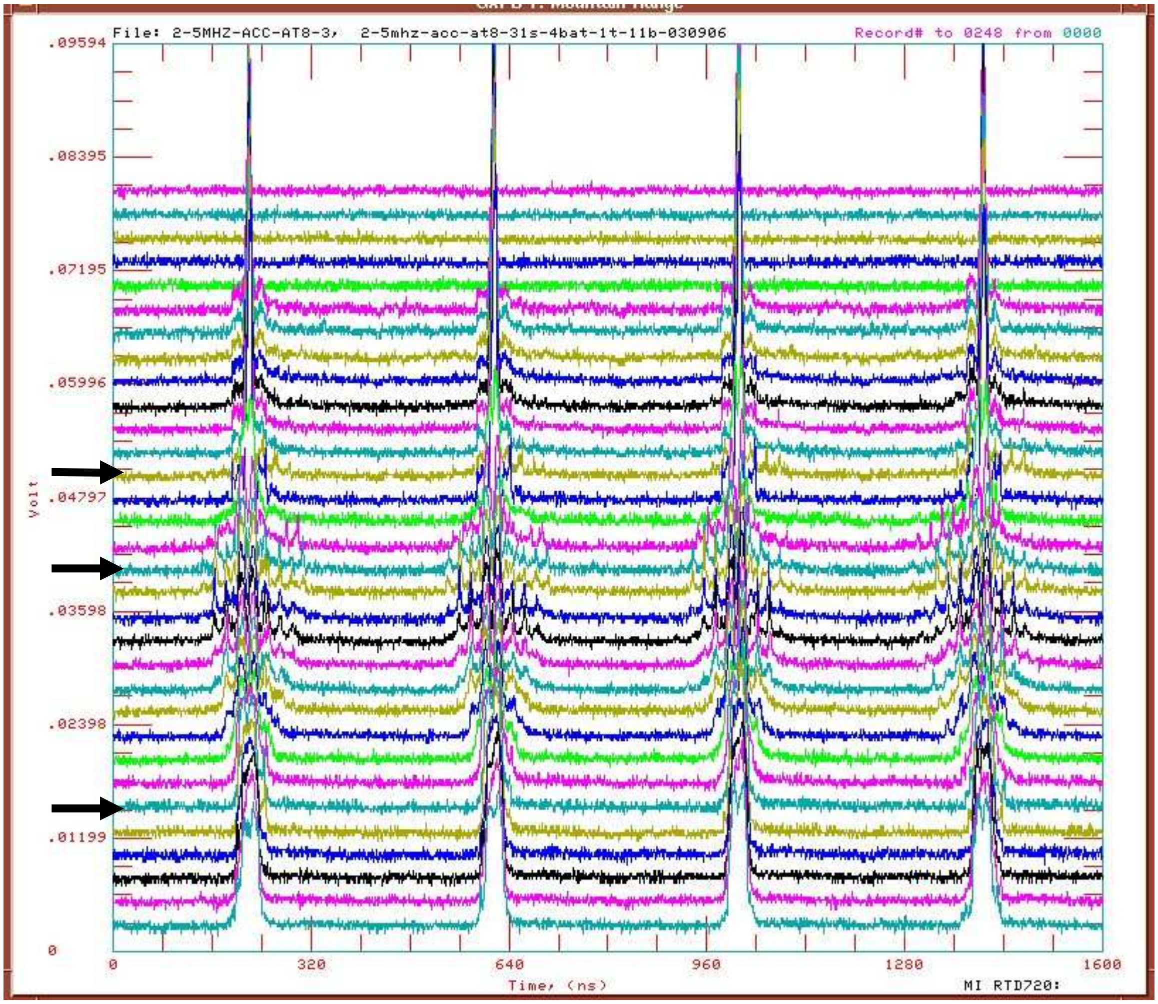

Figure 24. WCM data for four bunches around the bunch rotation and capture in 53 MHz rf buckets. The time gap between the traces is 11.2 msec. The first quarter synchrotron oscillation in a 4kV 2.5MHz rf bucket starts at about 56 msec from the lowest trace(lowest arrow). After 112 msec, (middle arrow) 2nd rotation commences in 60kV bucket which lasts for about 30 msec (3rd arrow). The 2.5 MHz feed back and feed-forward beam-loading compensation were on but not optimized. The 53 MHz feed back was on but not optimized for 2.5 MHz acceleration. The 53MHz feed-forward compensation was not turned on during this measurement.

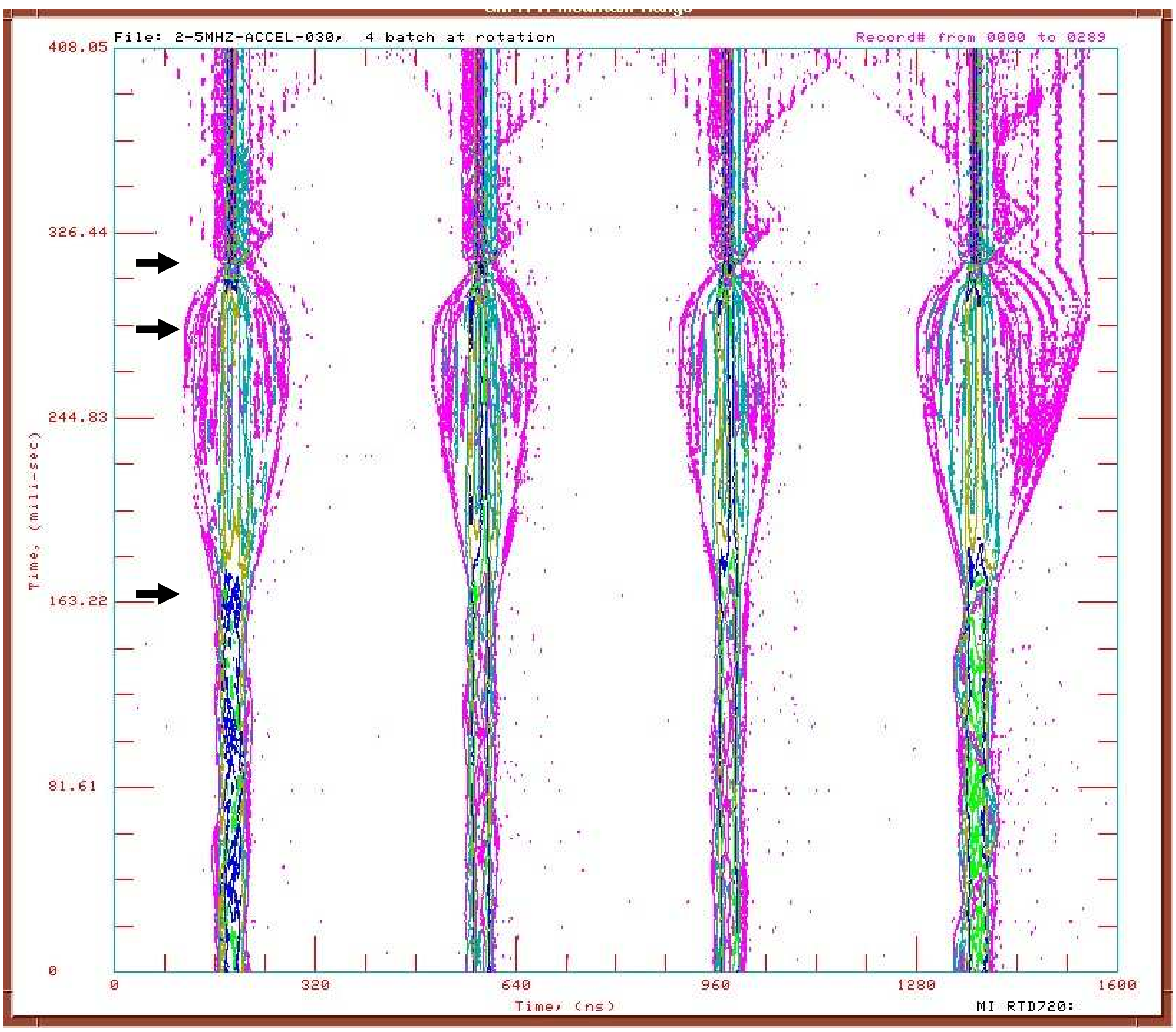

Figure 25. Same data as shown in figure 24, except, this data is contour plot. The difference between individual bunch behaviors is rather clear in this view.

b. Data Analysis

The longitudinal emittances of the beam at injection energy and the flat-top energy of 150 GeV are determined by measuring the bunch lengths and the rf voltages. The longitudinal emittance ε_l of a bunch in a stationary rf bucket with peak rf voltage Vrf is given by [16],

$$\varepsilon_l = 4\sqrt{\frac{2eV_{rf}R^2E_s}{2\pi h^3c^2\eta}}\int_0^Q\sqrt{\cos(x)-\cos Q}\,dx \qquad \cdots(1)$$

where, R, E_s, h, c, η, Q and ϕ_s are, respectively, MI radius, synchronous energy of the particle, harmonic number, velocity of the light, slip factor (which is a function of the energy), half bunch-length (in radian) and rf phase of the bunch (for stationary bucket it is 0 deg for energy below transition energy and 180 deg for beam energy above transition).

The Table V lists the measured longitudinal emittance from the data taken recently. These data were taken after optimizing the transition crossing and harmonic transfer at 27 GeV for the case with 4-bunch acceleration and 60E9 proton/bunch. Hence, they are not optimized for the single bunch case or lower or higher intensity cases. In operation, we need to optimize for single bunch separately. For four- bunch 60E9 protons/bunch case, we see on the average about 42% emittance growth from 8 GeV to 27 GeV 53 MHz capture. On a separate study we observed about 30% growth in the single bunch acceleration case.

Table V. Longitudinal Emittance measurements at different stages of beam acceleration on the data taken before the September 2003 shut-down. Note that the MI 2.5 MHz acceleration was tuned well for 4 bunch with 60E9protons/2.5 MHz bunch case.

One Bunch Acceleration

		8.889 GeV, 50 kV, 2.514 MHz	**27 GeV, 57 kV, 2.526 MHz**		**27 GeV, 900 kV, 53.046 MHz**	
Booster bunches		**emit. before acceleration(eVs)**	**emit. before rotation(eVs)**	**emit. growth,%**	**emit. after capture(eVs)**	**emit.@ growth,%**
9		1.3	2.06	58	2.56	24
11		1.64	2.16	32	2.87	33
60E9p						

Four Bunch Acceleration

		8.889 GeV, 50 kV, 2.514 MHz	**27 GeV, 57 kV, 2.526 MHz**		**27 GeV, 900 kV, 53.046 MHz**	
Booster bunches	**2.5 MHz bunch**	**emit. before acceleration(eVs)**	**emit. before rotation(eVs)**	**emit. growth,%**	**after capture(eVs)**	**emit. growth,%**
5	1	0.87	1.34	54	1.92	43
20E9p/	2	0.82	1.34	63	1.61	20
bunch	3	0.8	1.42	78	1.61	13
	4	0.89	1.51	70	1.61	7
11	**1**	**1.86**	**2.59**	**39**	**2.56**	**0**
60E9p/	**2**	**1.82**	**2.27**	**25**	**2.24**	**0**
bunch	**3**	**1.82**	**2.37**	**30**	**2.87**	**21**
	4	**1.86**	**2.59**	**39**	**2.87**	**11**

Note: 5 to 10% of beam loss after 53 MHz capture at 27 GeV.

@ the best emittance preservation from 8 GeV to 27 GeV till the end of the harmonic transfer for a single bunch acceleration case was about 30%. For the case measured here the emittance growth is higher than 30% because the acceleration was tuned for 4-batch acceleration.

Summary of Beam Studies : We have carried out single- bunch and four-bunch acceleration in the MI with 2.5 MHz acceleration scheme. The initial longitudinal emittances were in the range of 0.8 eVs to about 2 eVs and bunch intensities in the range of 20E9 to 60E9 protons/bunch. The beam loading compensation systems was partially on. In case single-bunch acceleration, the best we have seen is about 30% emittance growth from 8 GeV to the end of harmonic transfer and ~5% beam captured in the neighboring 53MHz buckets (satellite) at 27 GeV. In the case of four-bunch acceleration we had about 45% emittance growth with about 5-10% beam missing from the central bunch. The majority of emittance growth was seen during transition crossing and at 27 GeV harmonic transfer due to phase shift arising from the beam loading.

c) Future Study Plans

In future we plan to continue the 2.5 MHz acceleration studies with a) 2.5 MHz and 53 MHz feed-back as well as feed-forward beam–loading compensation optimized. The maximum beam bunch intensity will be increased from 60E9 to 170E9. Next we plan for the following studies:

*Definition of a **Shift***: Duration of a shift is 2-3 hour with one study event per 120 sec.

Harmonic Transfer from h=28 to h=588:

The simulation studies have indicated that by performing quarter synchrotron rotation with about 15 kV and with a subsequent quarter rotation in 60 kV and repeating these steps at 27 GeV we can preserve longitudinal emittance also minimize the effect of 53 MHz rf wave. We plan this to be implemented. (~2-3 shifts)

Accelerate proton beam from 8 GeV to 150 GeV (6-7):

- TLG Module 197: Update TLG module 197 to a hold off time 13 sec.
- 53 MHz Acceleration only:
  I3, I2 tune and chromaticity tables: Extend the existing ramp to 150 GeV
    a) I3-correct 53 MHz rf voltages from 8 GeV to 150 GeV. BA~2-3 eVsec from 27 GeV to 150 GeV
    b) Set I6<6> for 53 MHz beam acceleration from 8 GeV to 150 GeV.
    c) I2 Tune table: Accelerate 20-30 bunches of 53 MHz from 8 GeV to 150 GeV. To set proper tune and chromaticity (we may have a small loss of beam at transition). Measure the orbit all the way up the 150 GeV using I39. Take flying wire data.
    (2-shifts)
- Combine 2.5 MHz Acceleration and 53 MHz Acceleration (2-shifts)

Pbar acceleration from 8 to 150 GeV: (1-2 shifts):

Studies with Pbars -coordinate with pbar group:

- Request for 2.5 MHz bunches from Accumulator Ring (ask to turn off ARF1)
- Several low intensity shots to tune injection phase angle. (possibly we can copy I6<23>)
- Tune transition crossing (should not be different from that for protons)
- Proper 2.5 MHz alignments
- Beam should get accelerated without any problems.

- Integrate this with collider operation

The estimated shifts are with out any contingency. In reality, we may need about 19-20 shifts which corresponds to about 40 hours of beam time of which 11% will be for the proposed study. These studies will be semi-parasitic.

7. Issues

Beam loading: We have to address beam loading of 2.5 MHz rf cavities as well as 53 MHz rf systems. We have made significant progress during the last one year. They need to be tuned for this case.

Low 53MHz rf voltage during 2.5MHz acceleration: The simulations suggest that the 53 MHz rf voltage components to be <400V during the 2.5 MHz acceleration and first rotation at 27 GeV. Presently we are paraphrasing down the 53MHz rf voltage to smallest possible value. This need to be quantified. Depending upon the performance of the HLRF there is some amount of day-by-day variation in the final rf voltage obtained by paraphrasing two groups. This stability issue is of a concern even in the standard pbar coalescing. This needs further rf study.

Transition crossing: This is a major issue in all proton synchrotrons. Since the (non-adiabatic+non-linear) time for the 2.5 MHz acceleration (with dp/dt=3.2 GeV/c/sec near transition energy) is about 150msec the precise timing of the transition rf phase jump is rather vague. A careful tuning is critical. There are some intensity dependent effect which arise from beam loading of 53MHz rf system.

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Appendix – I

Progress made in " pbar acceleration in the MI using 2.5MHz and 53MHz rf systems" after the October 2003 Beams Division Review

A Beams Division technical review was held in October 2003 to evaluate the status, better understand and prioritize the " pbar acceleration in the MI using 2.5MHz and 53MHz rf systems" project. The review committee was convinced that this scheme of pbar acceleration could yield significant improvement in Run II operation and strongly recommended pursuing the project and stated that attempt should be made to make the scheme operation by spring 2004.

Since the review we have made progress in 1) simulations as well as 2) experiment with beam. The simulation results are summarized in the following documents:

1. "Simulation of beam loading with the effects of feedback and feedforward compensations for the 2.5 Mhz acceleration in Main Injector," Vincent Wu, Chandra Bhat, Beams-doc-849-v10
2. "Simulation of Main Injector 2.5 MHz Pbar Acceleration with Space Charge and Beam Loading Effects," V.Wu, Beams-doc-762-8
3. "Simulations of Main Injector 2.5MHz pbar acceleration including the effect of a small 53 MHz voltage," Vincent Wu, October 2003, (unpublished).

All these simulations were carried out assuming acceleration of four 2.5MHz bunches with a maximum of 170E9pbar/ bunch. The simulations suggested that with beam-loading compensation system in place which would give a factor of five reduction in the beam induced voltage through the feed-back beam loading compensation and an effective reduction in beam charge by a factor of ten from feed-forward compensation on 2.5 MHz rf system., and for 53MHz rf system, at least a factor of five reduction in the beam induced voltage through the feed-back beam loading compensation and an effective reduction in beam charge by a factor of ten from feed-forward compensation we can keep emittance growth less than 35% from 8 to 150 GeV.

After the October shut-down we have also carried out experiments with beam, with partially commissioned beam–loading compensation both for 2.5MHz and 53 MHz systems. The beam is accelerated from 8 GeV to 150 GeV. The figure A1 shows beam transmission efficiency. For up to 80E9 beam particles per bunch we have reached ~100% efficiency. After the bunch rotation at 27 GeV the four bunches in 53MHz buckets are accelerated. The wall current monitor data at 150 GeV are shown in figure A2. The data analysis and upgrading the intensity are in progress.

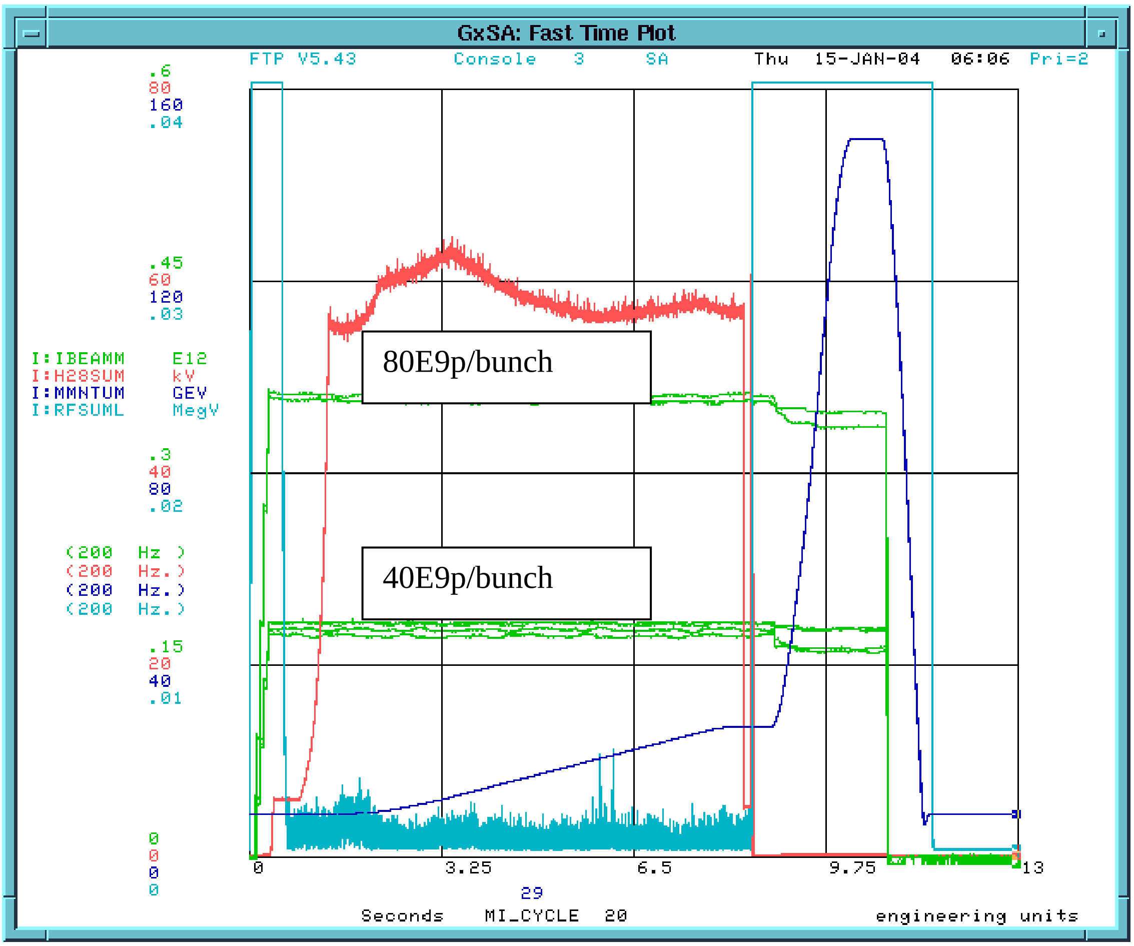

Figure A1. Four bunch acceleration from 8 GeV to 150 GeV. Green traces show beam, Red trace shows 2.5MHz programmed voltage, blue trace is the Main Injector ramp and cyan trace is 53MHz rf voltage.

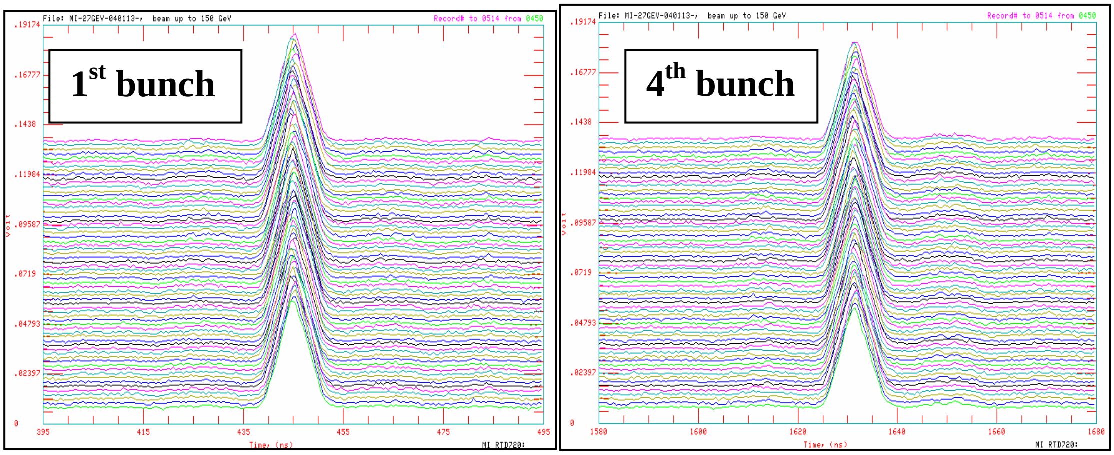

Figure A2. The wall current monitor data for the 1st (left figure) and the 4th bunch at 150 GeV (right figure). We see little satellites in both the cases. These traces correspond to the 80E9protons/bunch case in figure A1 with ~100% transmission efficiency.

In future we would like to fully commission the beam-loading compensation on this acceleration cycle. We need to further attention at transition crossing and harmonic transfer. We also would like to use the Main Injector longitudinal dampers.